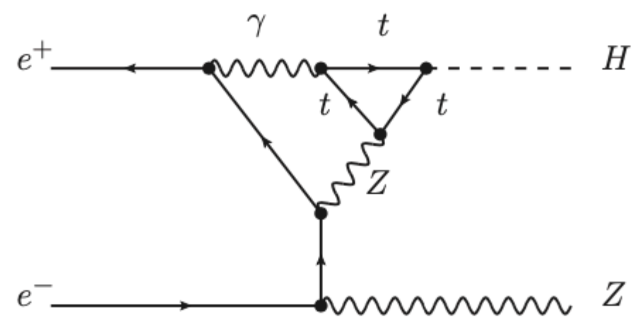
The WHIZARD generator: Status report, News and Plans

BASED UPON:

hep-ph/9607454 ; hep-ph/9806432 ; hep-ph/0102195 ; 0708.4241 ; 1112.1039 ; 1206.3700 ; 1411.3834; 1510.02739 ; 1609.03390 ; 1811.09711; 2108.05362; 2208.09438; 2304.09883

IN COLLABORATION WITH:

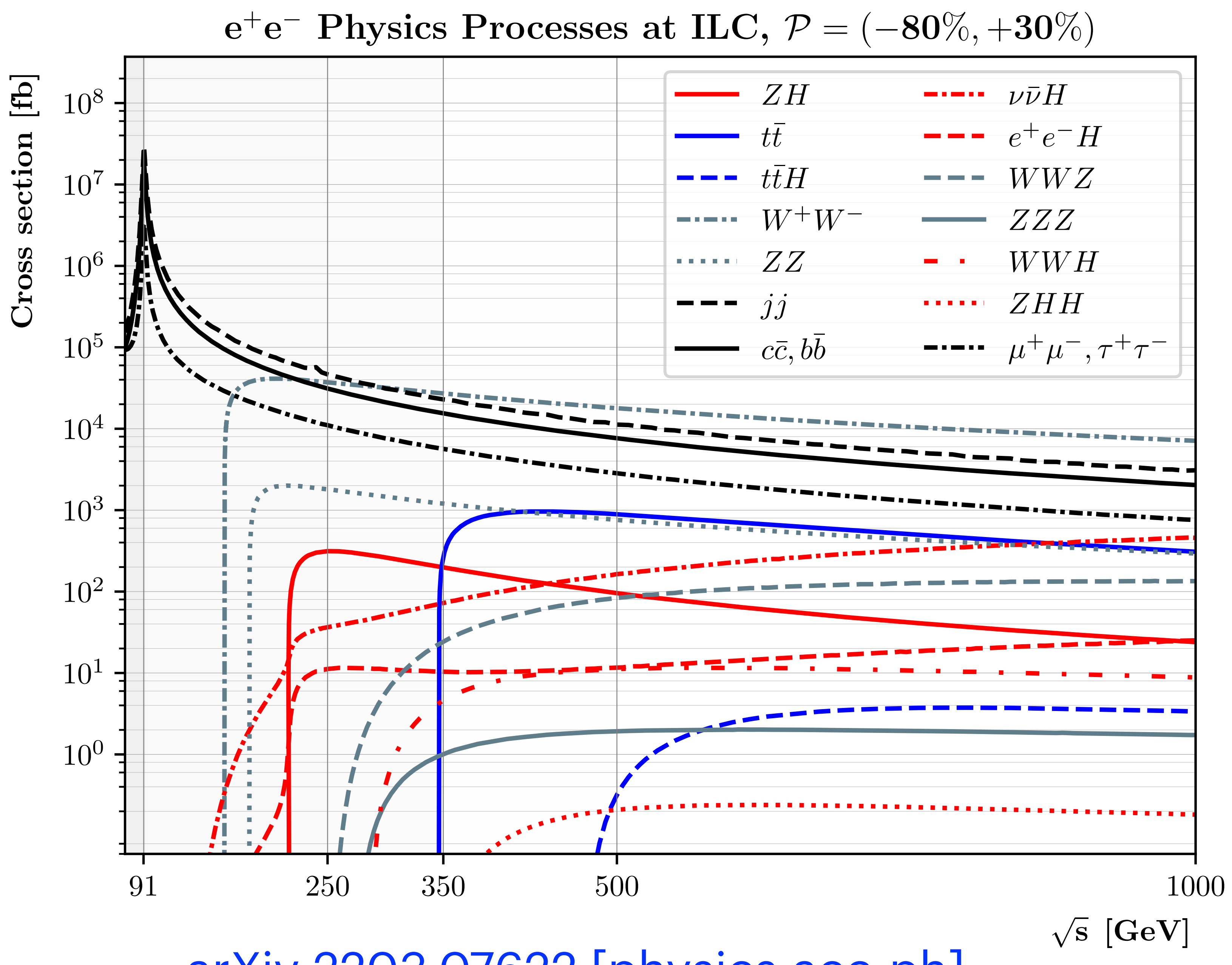
P. Bredt / M. Höfer / W. Kilian / M. Löschner / K. Mękała / T. Ohl / T. Striegl / A.F. Żarnecki



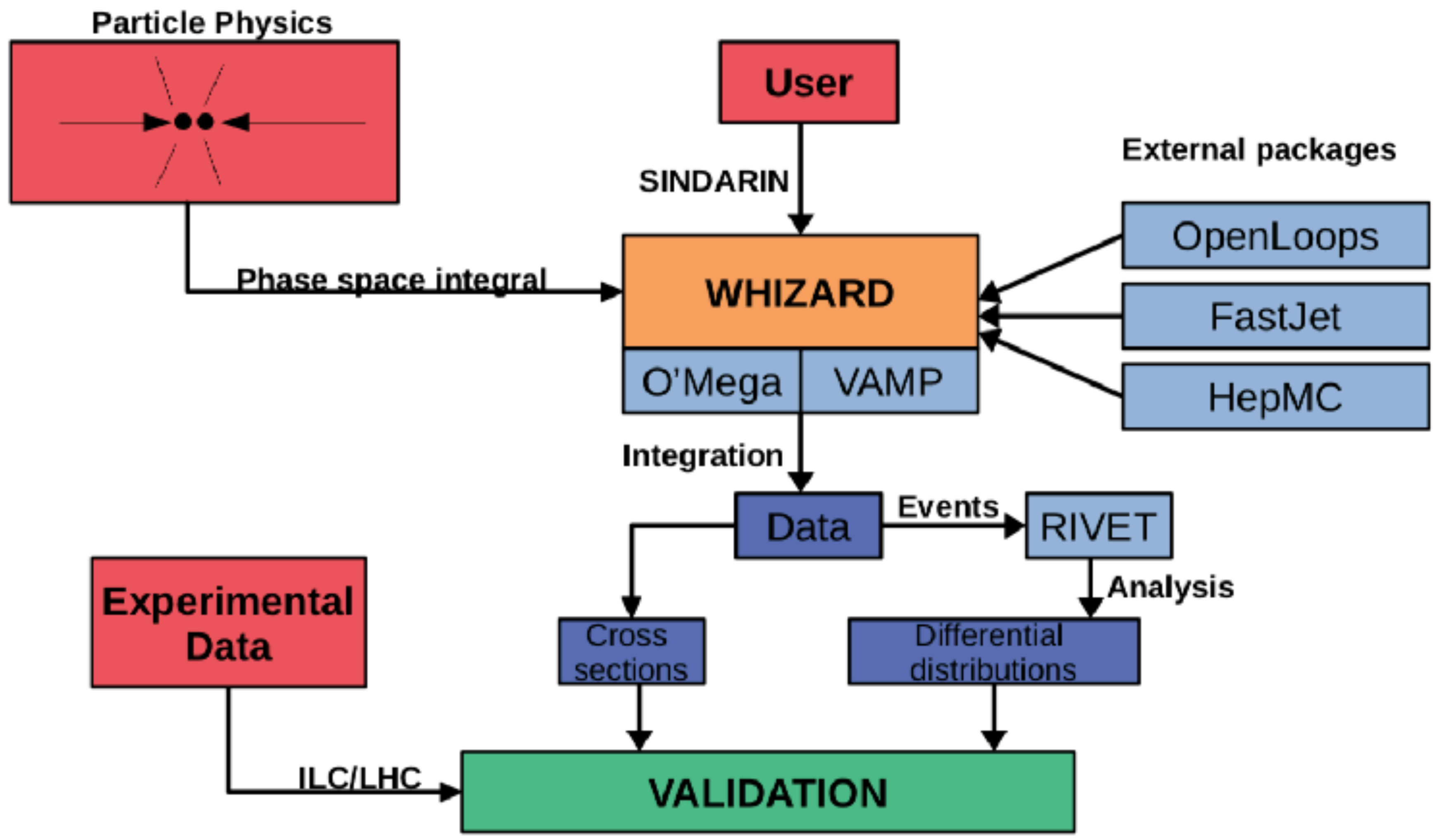
Jürgen R. Reuter

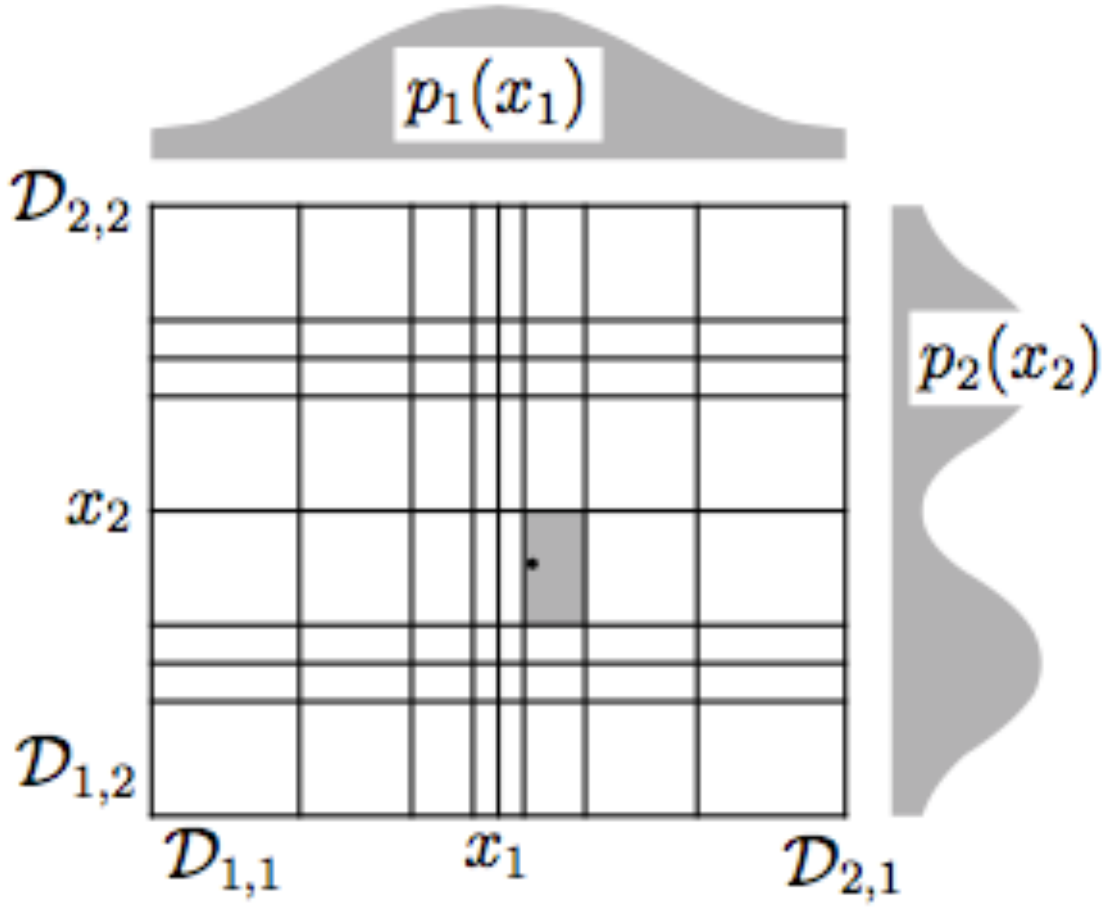
WHIZARD Overview (I)

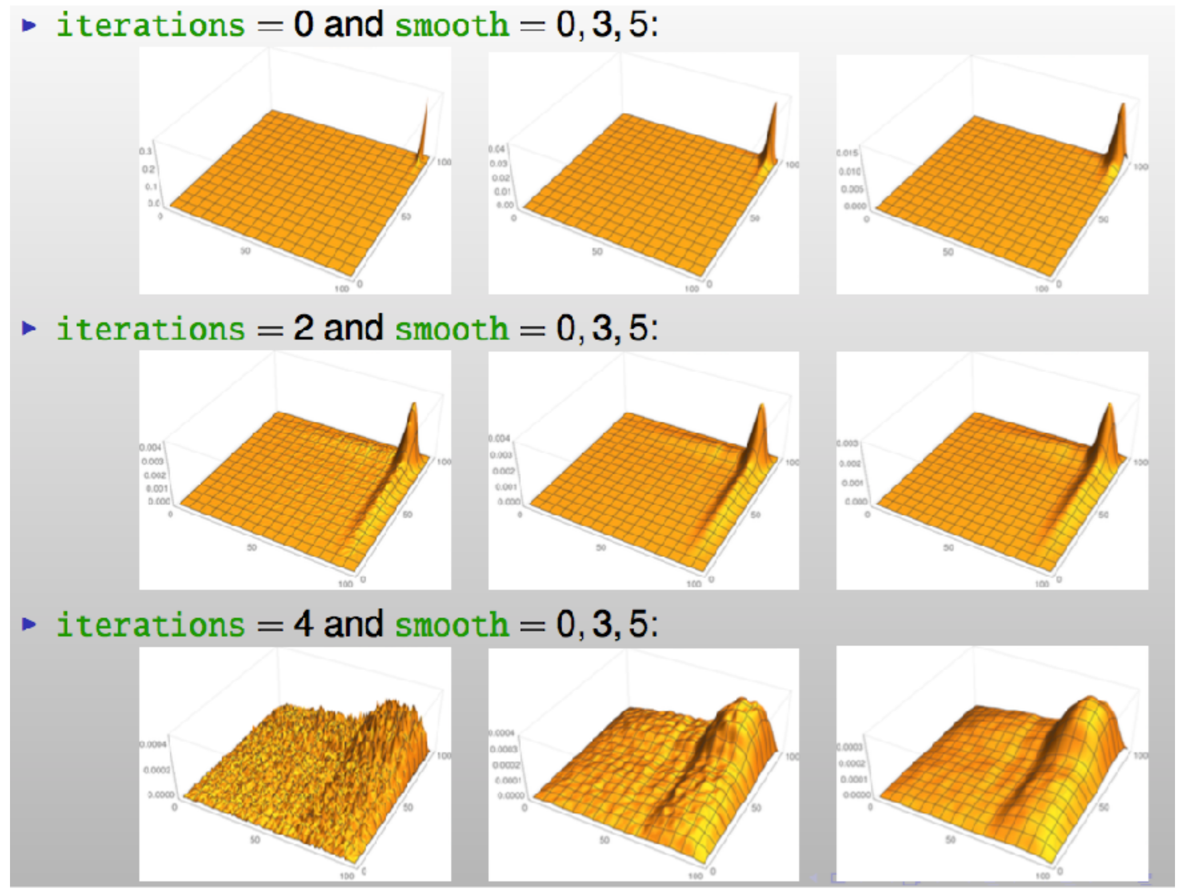
- Complete MC event generator for all colliders: v3 released 27.4.2021
- Hard matrix elements @ LO internally (O'Mega)
- Hard matrix elements @ NLO externally (OpenLoops, Recola, GoSam,...)
- Parton shower internal+external, hadronization external
- Dedicated interfaces to Pythia6, Pythia8 , Tauola, ...
- Lepton collider beam simulations (Gaussian spread, parameterized fit, beam event files, 2d-histogram adapted, smoothened, photon collisions):



arXiv:2203.07622 [physics.acc-ph]







↪ Talk by Thorsten Ohl 06/2023: https://indico.cern.ch/event/1266492/

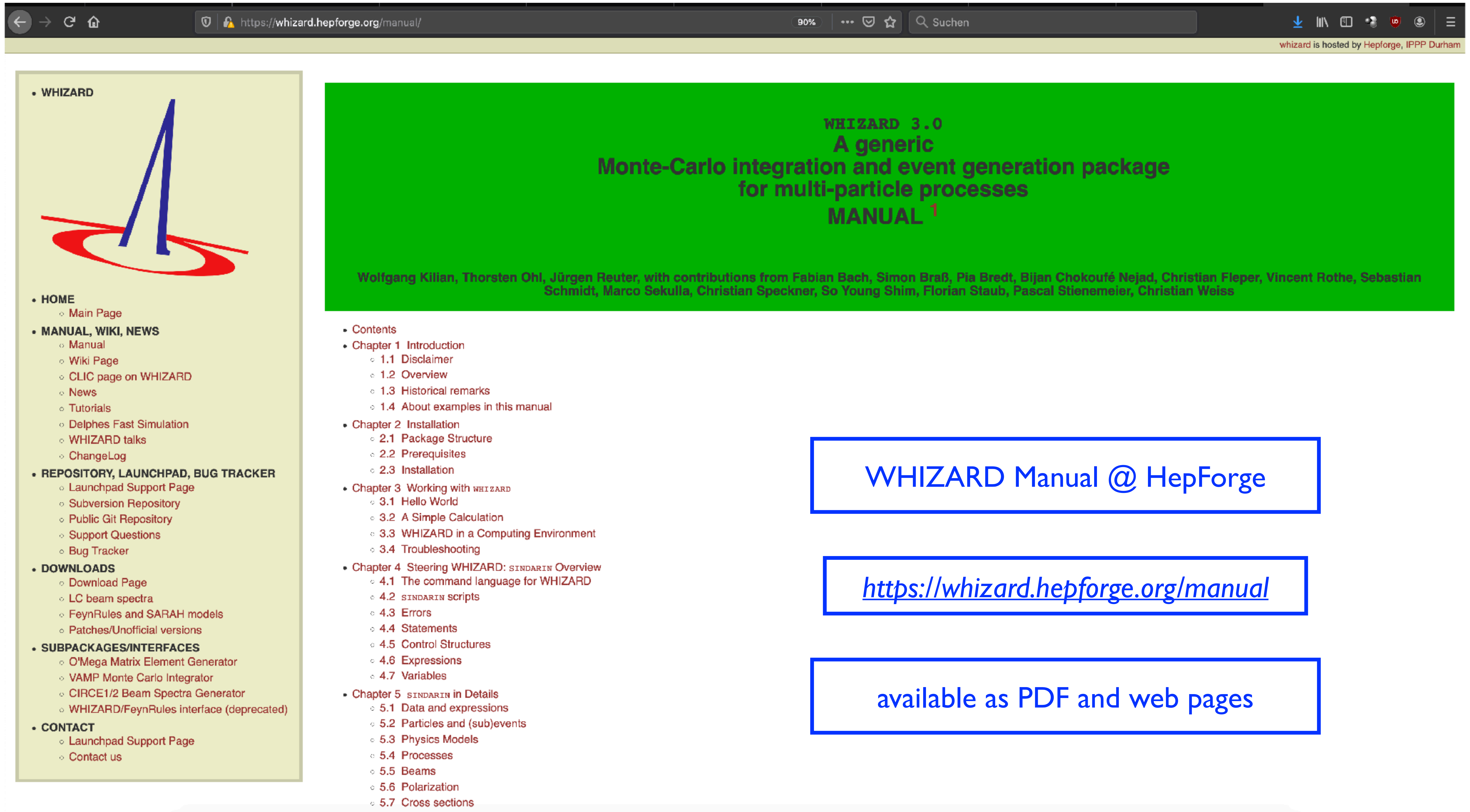
WHIZARD Overview (II)


```
model = NMSSM
process susyprod = e1, E1 => stau1, Stau1
process staudec = stau1 => neu1, e3

sqrts = 250 GeV
beams = e1, E1 => circe2 => isr
beams_pol_density = @(-1), @(+1)
beams_pol_fraction = 80%, 30%

n_events = 10000
sample_format = lhef, stdhep, hepmc
simulate (susyprod)
```

- Collider setup: arbitrarily polarized beams, crossing angle, asymmetric beams
- Event formats available: `LHA`, `LHE(v1-3)`, `HepMC2`, `HepMC3(RootIO)`, `LCIO`, EDM4HEP (w.i.p.)!
- Factorized processes (`unstable` feature, NWA, specific decay helicity, polarized resonance decays)
- Automated calculation of BRs of unstable particles, BRs can be set explicitly, e.g. to (N)NLO values
- BSM models through UFO interface (cf. later)
- Special treatment of top threshold physics (cf. later)
- Reweighting / recasting processes + multiple weights/observables
- **Focus here new developments: Completion NLO automation, NLO matching, high-performance, revalidations, new physics implementations: long-lived particles, initial-state QED treatment, EW PDFs etc.**

WHIZARD: User support / bug tracker

WHIZARD v3.1.4 (8.11.2023) https://launchpad.net/whizard whizard@desy.de



WHIZARD Manual @ HepForge

https://whizard.hepforge.org/manual

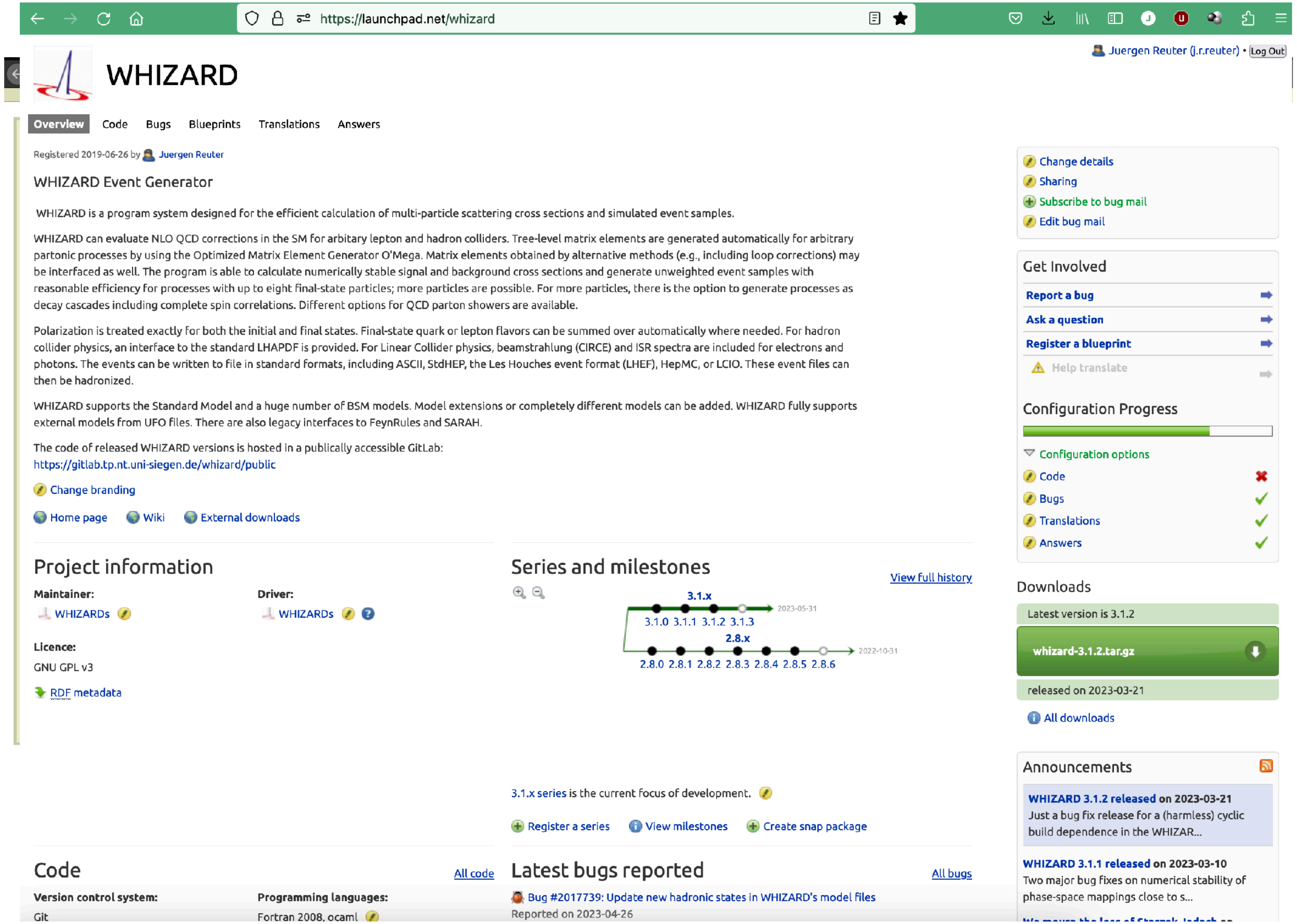
available as PDF and web pages

WHIZARD Tutorial

e.g. for Snowmass, 20.9.2020: https://indico.fnal.gov/event/45413/

WHIZARD: User support / bug tracker

WHIZARD v3.1.4 (8.11.2023) https://launchpad.net/whizard whizard@desy.de



https://launchpad.net/whizard

Juergen Reuter (j.r.reuter) • Log Out

WHIZARD

Overview Code Bugs Blueprints Translations Answers

Registered 2019-06-26 by Juergen Reuter

WHIZARD Event Generator

WHIZARD is a program system designed for the efficient calculation of multi-particle scattering cross sections and simulated event samples.

WHIZARD can evaluate NLO QCD corrections in the SM for arbitary lepton and hadron colliders. Tree-level matrix elements are generated automatically for arbitrary partonic processes by using the Optimized Matrix Element Generator O'Mega. Matrix elements obtained by alternative methods (e.g., including loop corrections) may be interfaced as well. The program is able to calculate numerically stable signal and background cross sections and generate unweighted event samples with reasonable efficiency for processes with up to eight final-state particles; more particles are possible. For more particles, there is the option to generate processes as decay cascades including complete spin correlations. Different options for QCD parton showers are available.

Polarization is treated exactly for both the initial and final states. Final-state quark or lepton flavors can be summed over automatically where needed. For hadron collider physics, an interface to the standard LHAPDF is provided. For Linear Collider physics, beamstrahlung (CIRCE) and ISR spectra are included for electrons and photons. The events can be written to file in standard formats, including ASCII, StdHEP, the Les Houches event format (LHEF), HepMC, or LCIO. These event files can then be hadronized.

WHIZARD supports the Standard Model and a huge number of BSM models. Model extensions or completely different models can be added. WHIZARD fully supports external models from UFO files. There are also legacy interfaces to FeynRules and SARAH.

The code of released WHIZARD versions is hosted in a publically accessible GitLab:
https://gitlab.tp.nt.uni-siegen.de/whizard/public

Change branding

Home page Wiki External downloads

Project information

Maintainer: WHIZARDs

Driver: WHIZARDs

Licence: GNU GPL v3

RDF metadata

Series and milestones

View full history

3.1.x: 3.1.0 3.1.1 3.1.2 3.1.3 (2023-05-31)

2.8.x: 2.8.0 2.8.1 2.8.2 2.8.3 2.8.4 2.8.5 2.8.6 (2022-10-31)

3.1.x series is the current focus of development.

Register a series View milestones Create snap package

Code All code

Version control system: Git

Programming languages: Fortran 2008, ocaml

Latest bugs reported All bugs

Bug #2017739: Update new hadronic states in WHIZARD's model files
Reported on 2023-04-26

Change details
Sharing
Subscribe to bug mail
Edit bug mail

Get Involved

Report a bug
Ask a question
Register a blueprint
Help translate

Configuration Progress

Configuration options
Code
Bugs
Translations
Answers

Downloads

Latest version is 3.1.2

whizard-3.1.2.tar.gz

released on 2023-03-21

All downloads

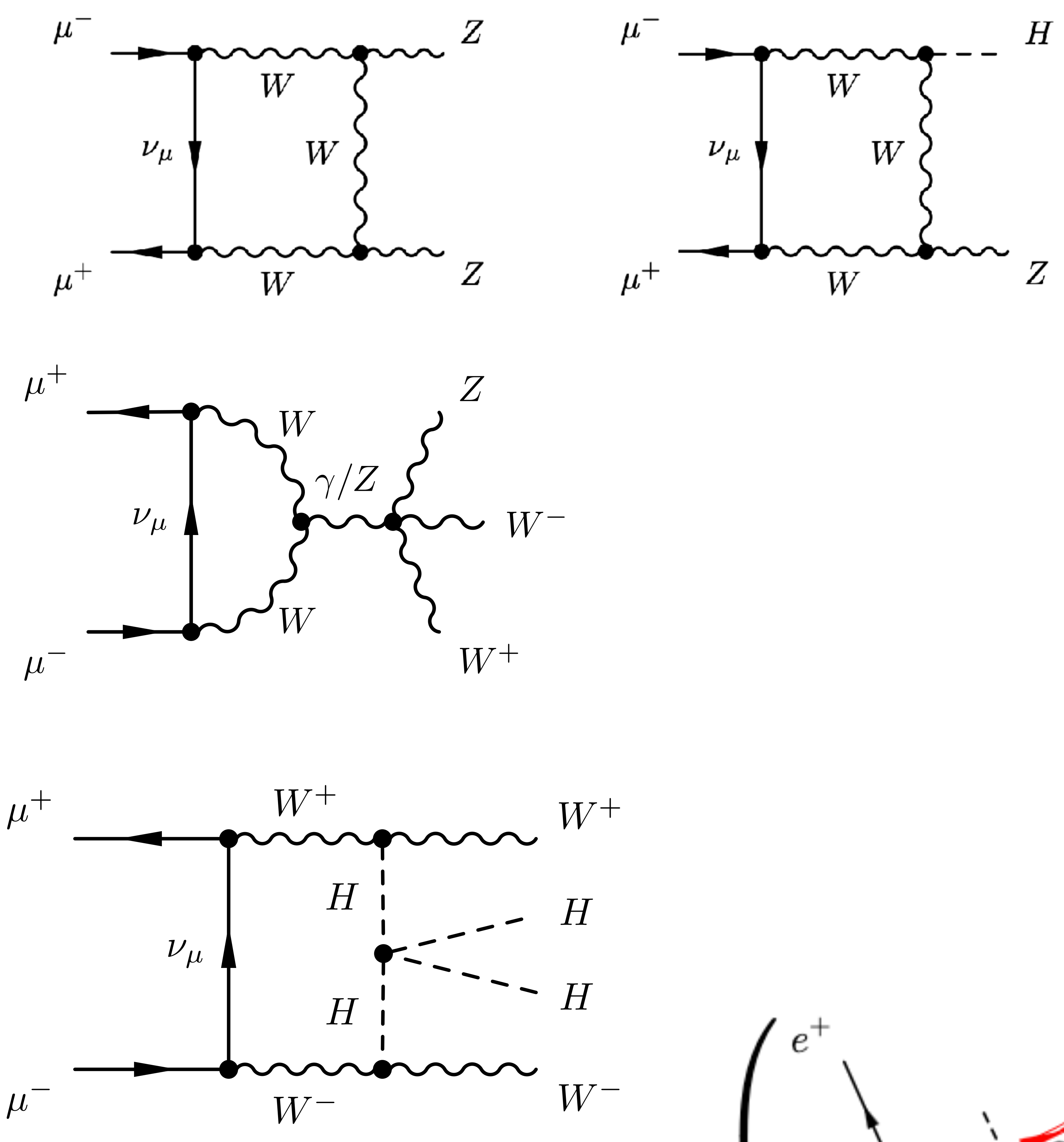
Announcements

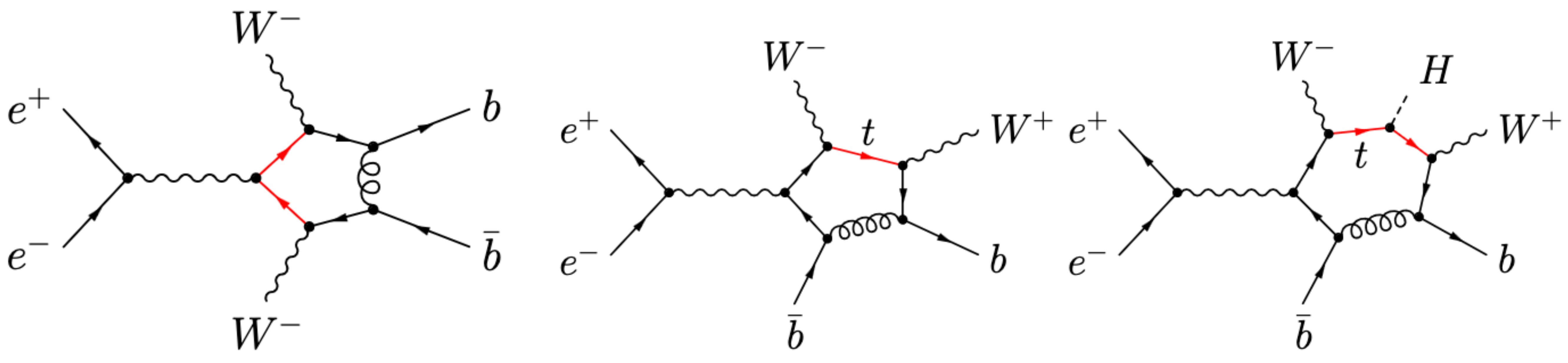
WHIZARD 3.1.2 released on 2023-03-21
Just a bug fix release for a (harmless) cyclic build dependence in the WHIZAR...

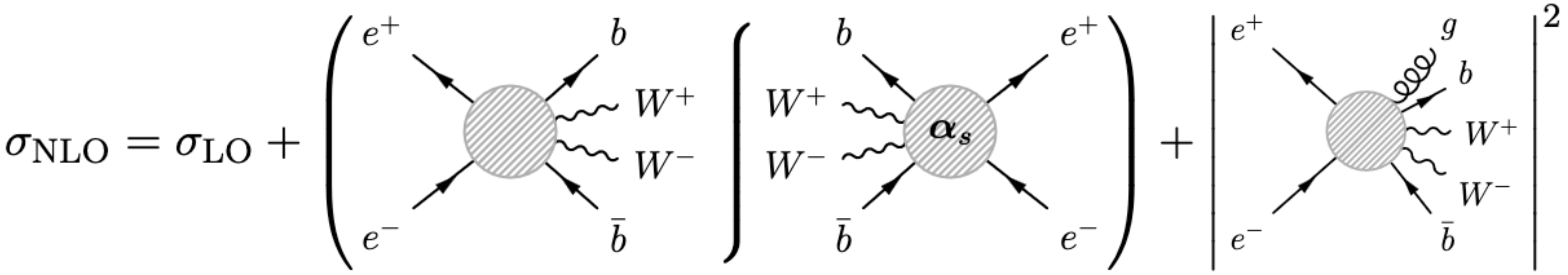
WHIZARD 3.1.1 released on 2023-03-10
Two major bug fixes on numerical stability of phase-space mappings close to s...

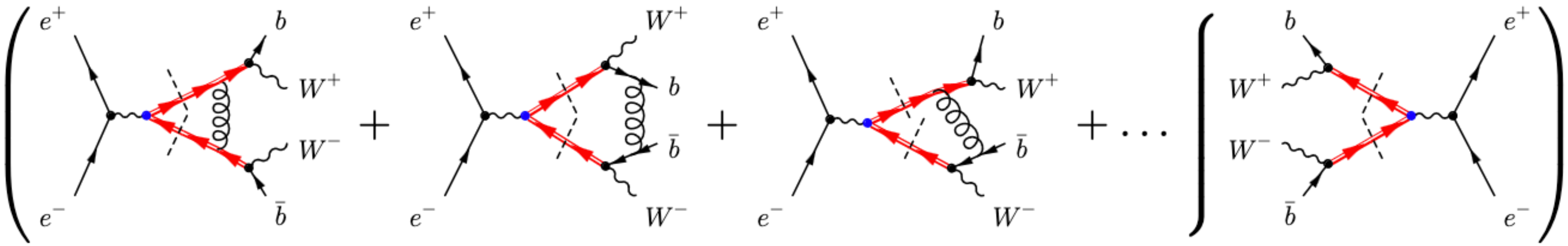
- 706468 Gaussian or Breit wigner distribution
- 706412 Syntax for forcing two identical particles to different final states
- 706411 Various errors when generating events with (b) jets in the final state
- 706291 Error while generating NLO events with polarized e+ e- beams
- 706197 how to uninstall whizard
- 706070 default cuts
- 706008 issues with installing whizard with openloops

WHIZARD NLO Automation: Loops & Legs







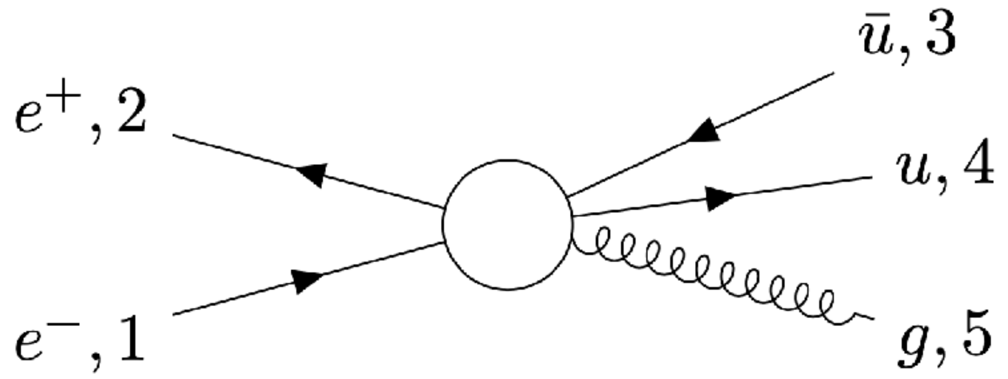


WHIZARD NLO Automation: Loops & Legs

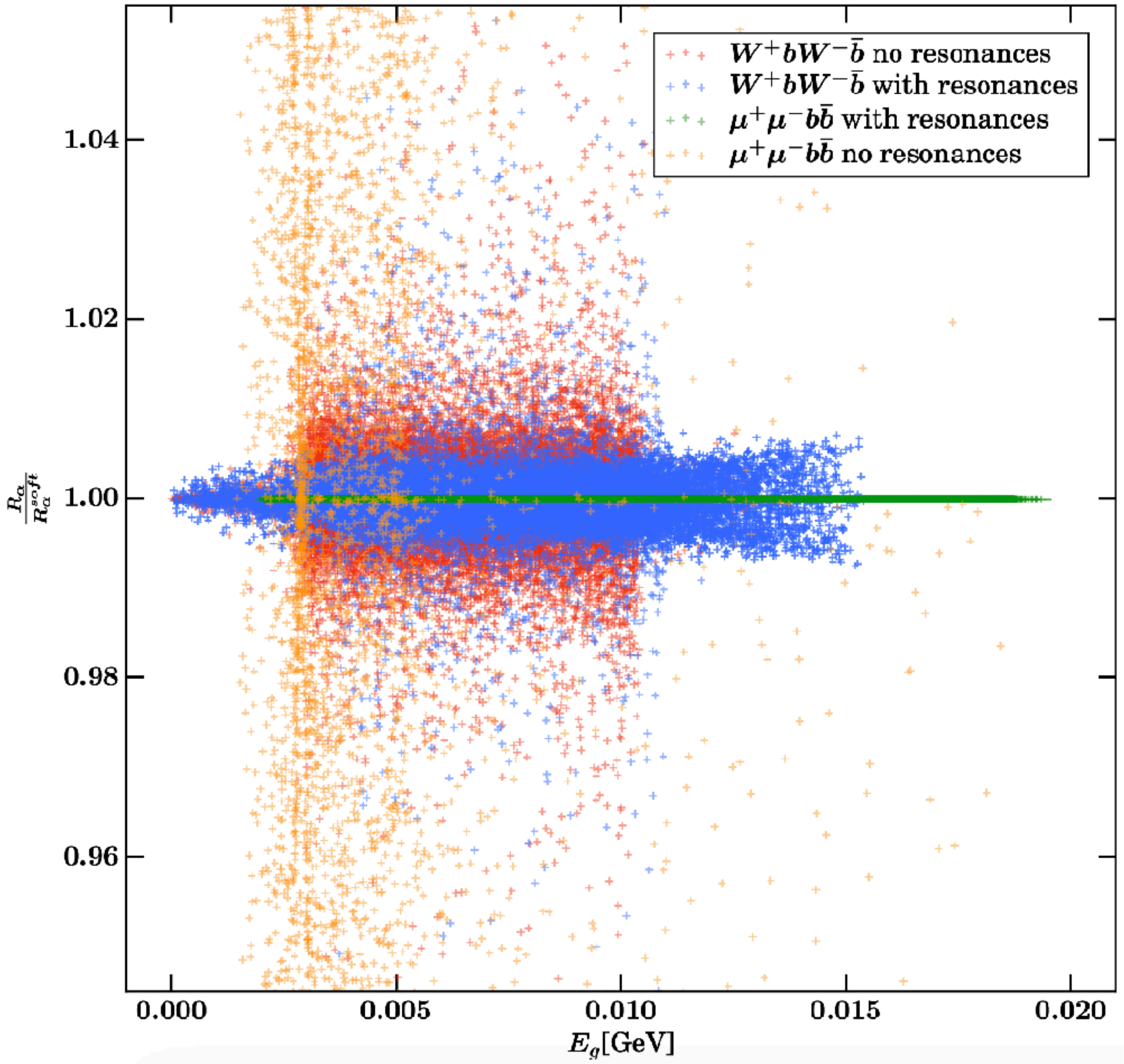
- NLO SM automation for lepton-/hadron colliders completed 2022 — Chokoufé; Weiss 2017; Rothe 2021; Stienemeier; Bredt 2022
- FKS subtraction, NLO matrix elements from OpenLoops/Recola/GoSam/...
- also: resonance-aware FKS subtraction — cf. Ježo/Nason, arXiv:1509.09071; Chokoufé, 2017
- Setup for automatic differential fixed-order results (histogrammed distributions)
- Photon isolation, photon recombination, light-, b-, c-jet selection; loop-induced processes

$$\sigma_{\text{NLO}} = \int d\Phi_n \mathcal{B} + \int d\Phi_{n+1} \underbrace{\left[\mathcal{R}(\Phi_{n+1}) - d\sigma_S(\Phi_{n+1})\right]}_{\text{finite by construction}} + \underbrace{\int d\Phi_n \mathcal{V} + \int d\Phi_n d\sigma_{S,\text{int}}}_{\text{finite by KLN}}$$

$\mathcal{B}$: Born, $\mathcal{R}$: Real emission, $\mathcal{V}$: Virtual



For NLO QCD possible singular regions: $(i,j) \in \{(3,5),(4,5)\}$



Some examples for NLO results

ee @ 1 TeV, NLO QCD

Process	WHIZARD+OpenLoops σ_{LO} [fb]	σ_{NLO} [fb]
$e^+e^- \to jj$	622.737(8)	639.39(5)
$e^+e^- \to jjj$	340.6(5)	317.8(5)
$e^+e^- \to jjjj$	105.0(3)	104.2(4)
$e^+e^- \to jjjjj$	22.33(5)	24.57(7)
$e^+e^- \to jjjjjj$	3.583(17)	4.46(4)

$e^+e^- \to t\bar{t}$	166.37(12)	174.55(20)
$e^+e^- \to t\bar{t}j$	48.12(5)	53.41(7)
$e^+e^- \to t\bar{t}jj$	8.592(19)	10.526(21)
$e^+e^- \to t\bar{t}jjj$	1.035(4)	1.405(5)
$e^+e^- \to t\bar{t}t\bar{t}$	$0.6388(8) \cdot 10^{-3}$	$1.1922(11) \cdot 10^{-3}$
$e^+e^- \to t\bar{t}t\bar{t}j$	$2.673(7) \cdot 10^{-5}$	$5.251(11) \cdot 10^{-5}$
$e^+e^- \to t\bar{t}H$	2.020(3)	1.912(3)
$e^+e^- \to t\bar{t}Hj$	$2.536(4) \cdot 10^{-1}$	$2.657(4) \cdot 10^{-1}$
$e^+e^- \to t\bar{t}Hjj$	$2.646(8) \cdot 10^{-2}$	$3.123(9) \cdot 10^{-2}$
$e^+e^- \to t\bar{t}Z$	4.638(3)	4.937(3)
$e^+e^- \to t\bar{t}Zj$	$6.027(9) \cdot 10^{-1}$	$6.921(11) \cdot 10^{-1}$
$e^+e^- \to t\bar{t}Zjj$	$6.436(21) \cdot 10^{-2}$	$8.241(29) \cdot 10^{-2}$
$e^+e^- \to t\bar{t}W^\pm jj$	$2.387(8) \cdot 10^{-4}$	$3.716(10) \cdot 10^{-4}$
$e^+e^- \to t\bar{t}HZ$	$3.623(19) \cdot 10^{-2}$	$3.584(19) \cdot 10^{-2}$
$e^+e^- \to t\bar{t}ZZ$	$3.788(6) \cdot 10^{-2}$	$4.032(7) \cdot 10^{-2}$
$e^+e^- \to t\bar{t}HH$	$1.3650(15) \cdot 10^{-2}$	$1.2168(16) \cdot 10^{-2}$
$e^+e^- \to t\bar{t}W^+W^-$	$1.3672(21) \cdot 10^{-1}$	$1.5385(22) \cdot 10^{-1}$

pp @ 13 TeV, NLO QCD

Process Vector boson (pair) plus jets	WHIZARD σ_{LO}[fb]	σ_{NLO}[fb]	K
$pp \to W^\pm$ *	$1.3749(8) \cdot 10^8$	$1.7696(10) \cdot 10^8$	1.29
$pp \to W^\pm j$ *	$2.046(3) \cdot 10^7$	$2.854(5) \cdot 10^7$	1.39
$pp \to W^\pm jj$	$6.856(12) \cdot 10^6$	$7.814(27) \cdot 10^6$	1.14
$pp \to W^\pm jjj$ †	$1.840(5) \cdot 10^6$	$1.978(7) \cdot 10^6$	1.07
$pp \to Z$	$4.2541(3) \cdot 10^7$	$5.4086(16) \cdot 10^7$	1.27
$pp \to Zj$	$7.215(4) \cdot 10^6$	$9.733(10) \cdot 10^6$	1.35
$pp \to Zjj$	$2.364(5) \cdot 10^6$	$2.676(7) \cdot 10^6$	1.13
$pp \to Zjjj$	$6.381(23) \cdot 10^5$	$6.85(3) \cdot 10^5$	1.07
$pp \to W^+W^-(4f)$	$7.352(10) \cdot 10^4$	$10.268(11) \cdot 10^4$	1.40
$pp \to W^+W^-j(4f)$	$2.853(7) \cdot 10^4$	$3.733(7) \cdot 10^4$	1.31
$pp \to W^+W^-jj(4f)$ *	$1.150(5) \cdot 10^4$	$1.372(6) \cdot 10^4$	1.19
$pp \to W^+W^+jj$ *	$1.506(5) \cdot 10^2$	$2.235(7) \cdot 10^2$	1.48
$pp \to W^-W^-jj$	$6.772(24) \cdot 10^1$	$9.982(28) \cdot 10^1$	1.47
$pp \to ZW^\pm$	$2.780(5) \cdot 10^4$	$4.488(4) \cdot 10^4$	1.61
$pp \to ZW^\pm j$	$1.609(4) \cdot 10^4$	$2.0940(28) \cdot 10^4$	1.30
$pp \to ZW^\pm jj$	$8.06(3) \cdot 10^3$	$9.02(4) \cdot 10^3$	1.12
$pp \to ZZ$ *	$1.0969(10) \cdot 10^4$	$1.4183(11) \cdot 10^4$	1.29
$pp \to ZZj$	$3.667(9) \cdot 10^3$	$4.807(8) \cdot 10^3$	1.31
$pp \to ZZjj$ *	$1.356(6) \cdot 10^3$	$1.684(8) \cdot 10^3$	1.24

pp @ 13 TeV, NLO QCD/EW mixed

$pp \to t\bar{t}W^+$	$\alpha_s^n \alpha^m$	σ^{tot} [fb] MUNICH$_{\text{(CS)}}$	WHIZARD	σ^{sig} / dev MUNICH$_{\text{(CS)}}$-WHIZARD
LO$_{21}$	$\alpha_s^2\alpha$	$2.411403(1) \cdot 10^2$	$2.4114(1) \cdot 10^2$	0.72 / 0.003%
LO$_{12}$	$\alpha_s\alpha^2$	0.000	0.000	0.00 / 0.000%
LO$_{03}$	α^3	$2.31909(1) \cdot 10^0$	$2.3193(1) \cdot 10^0$	1.76 / 0.009%
δNLO$_{31}$	$\alpha_s^3\alpha$	$1.18993(2) \cdot 10^2$	$1.1905(5) \cdot 10^2$	1.06 / 0.048%
δNLO$_{22}$	$\alpha_s^2\alpha^2$	$-1.09511(9) \cdot 10^1$	$-1.0947(3) \cdot 10^1$	1.13 / 0.035%
δNLO$_{13}$	$\alpha_s\alpha^3$	$2.93251(3) \cdot 10^1$	$2.9334(8) \cdot 10^1$	1.14 / 0.030%
δNLO$_{04}$	α^4	$5.759(3) \cdot 10^{-2}$	$5.756(4) \cdot 10^{-2}$	0.58 / 0.049%

μμ @ 3 TeV, NLO EW

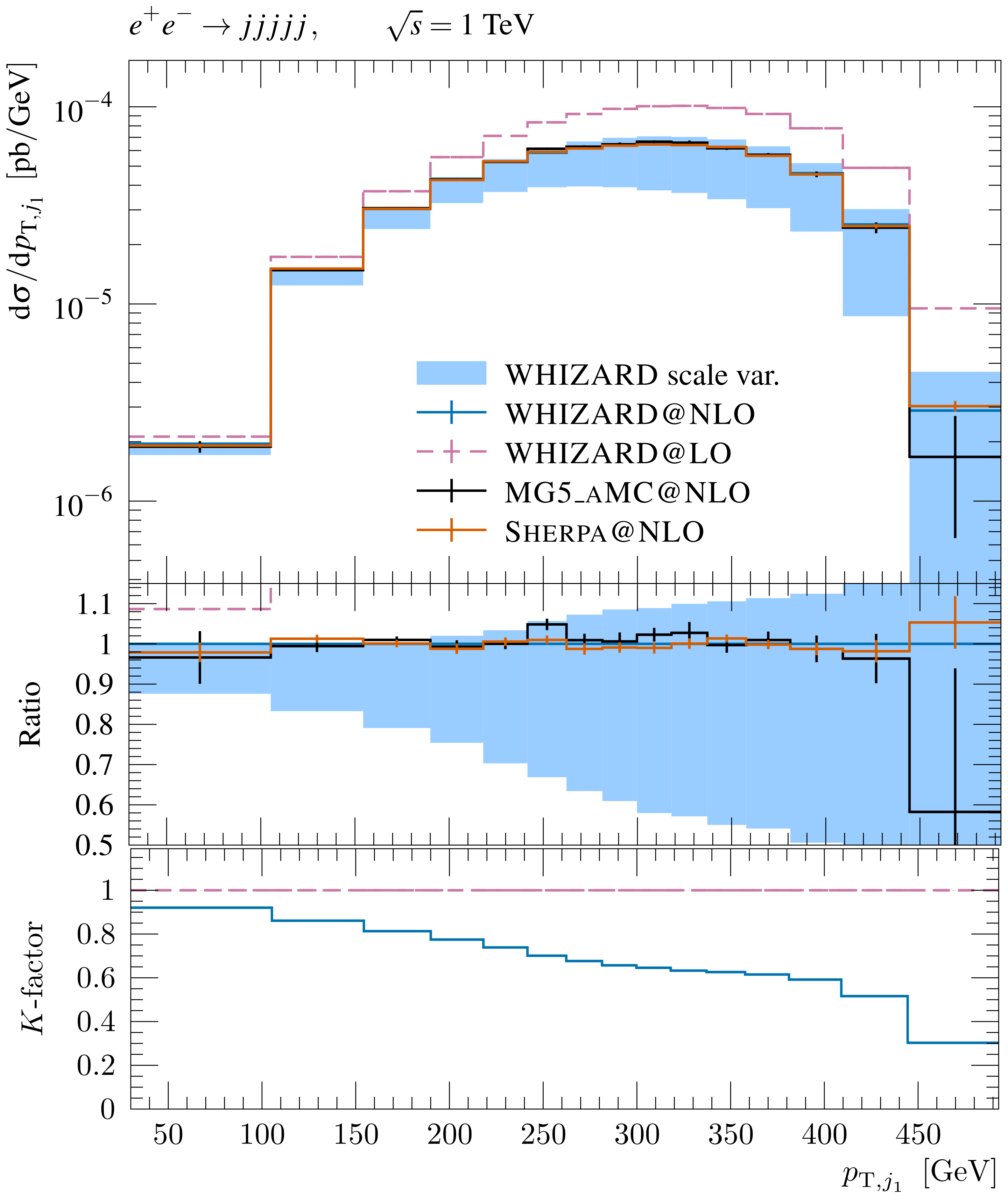
$\mu^+\mu^- \to X, \sqrt{s} =$	$\sigma_{\text{LO}}^{\text{incl}}$ [fb]	$\sigma_{\text{NLO}}^{\text{incl}}$ [fb]	δ_{EW} [%]
W^+W^-	$4.6591(2) \cdot 10^2$	$4.847(7) \cdot 10^2$	+4.0(2)
ZZ	$2.5988(1) \cdot 10^1$	$2.656(2) \cdot 10^1$	+2.19(6)
HZ	$1.3719(1) \cdot 10^0$	$1.3512(5) \cdot 10^0$	−1.51(4)
HH	$1.60216(7) \cdot 10^{-7}$	$5.66(1) \cdot 10^{-7}$ *	
W^+W^-Z	$3.330(2) \cdot 10^1$	$2.568(8) \cdot 10^1$	−22.9(2)
W^+W^-H	$1.1253(5) \cdot 10^0$	$0.895(2) \cdot 10^0$	−20.5(2)
ZZZ	$3.598(2) \cdot 10^{-1}$	$2.68(1) \cdot 10^{-1}$	−25.5(3)
HZZ	$8.199(4) \cdot 10^{-2}$	$6.60(3) \cdot 10^{-2}$	−19.6(3)
HHZ	$3.277(1) \cdot 10^{-2}$	$2.451(5) \cdot 10^{-2}$	−25.2(1)
HHH	$2.9699(6) \cdot 10^{-8}$	$0.86(7) \cdot 10^{-8}$ *	
$W^+W^-W^+W^-$	$1.484(1) \cdot 10^0$	$0.993(6) \cdot 10^0$	−33.1(4)
W^+W^-ZZ	$1.209(1) \cdot 10^0$	$0.699(7) \cdot 10^0$	−42.2(6)
W^+W^-HZ	$8.754(8) \cdot 10^{-2}$	$6.05(4) \cdot 10^{-2}$	−30.9(5)
W^+W^-HH	$1.058(1) \cdot 10^{-2}$	$0.655(5) \cdot 10^{-2}$	−38.1(4)
$ZZZZ$	$3.114(2) \cdot 10^{-3}$	$1.799(7) \cdot 10^{-3}$	−42.2(2)
$HZZZ$	$2.693(2) \cdot 10^{-3}$	$1.766(6) \cdot 10^{-3}$	−34.4(2)
$HHZZ$	$9.828(7) \cdot 10^{-4}$	$6.24(2) \cdot 10^{-4}$	−36.5(2)
$HHHZ$	$1.568(1) \cdot 10^{-4}$	$1.165(4) \cdot 10^{-4}$	−25.7(2)

ee @ .25 TeV, NLO EW, pol.av. + pol.

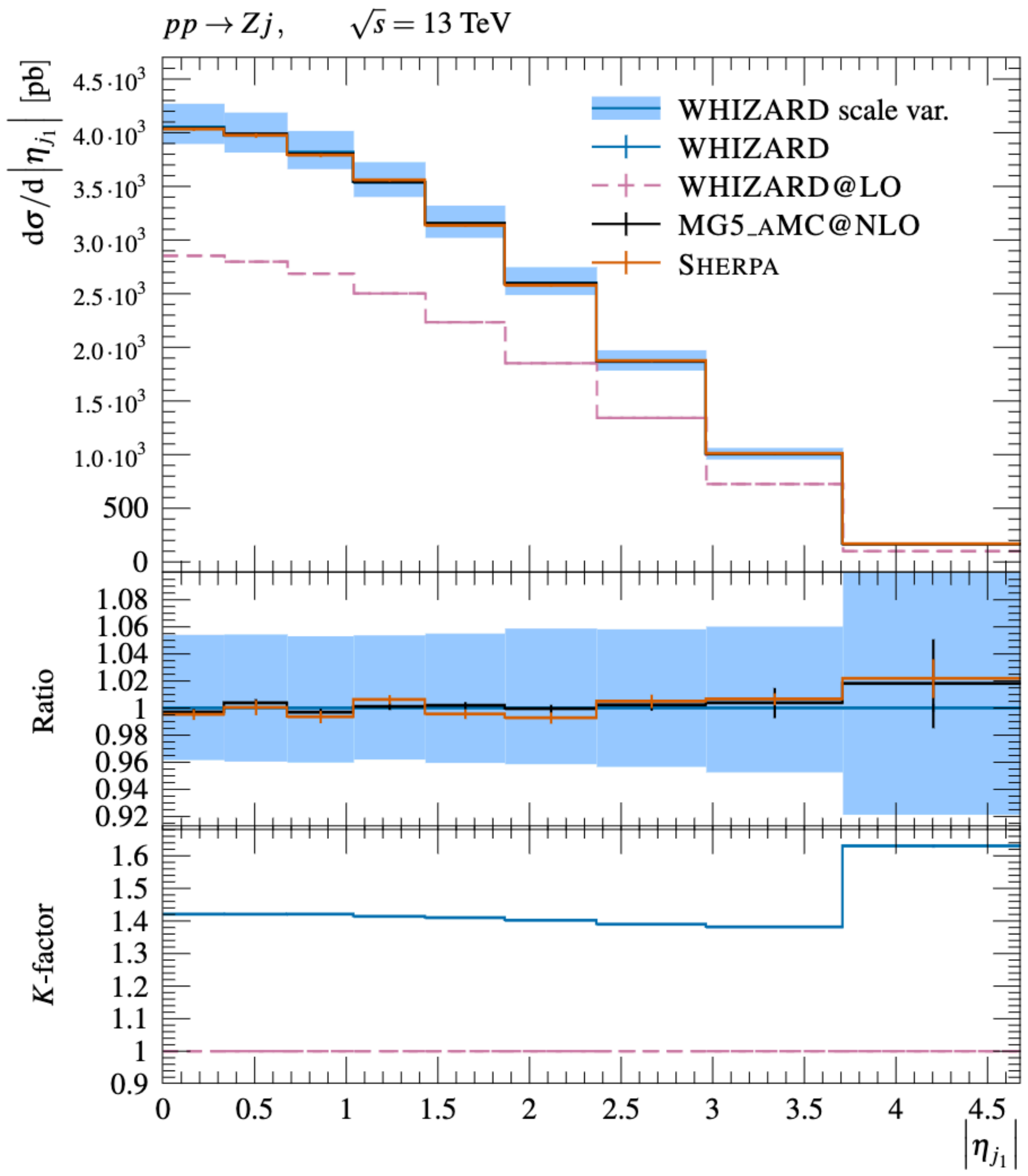
$\sqrt{s}$ [GeV]	MCSANCee[37] $\sigma_{\text{LO}}^{\text{tot}}$ [fb]	$\sigma_{\text{NLO}}^{\text{tot}}$ [fb]	WHIZARD+RECOLA $\sigma_{\text{LO}}^{\text{tot}}$ [fb]	$\sigma_{\text{NLO}}^{\text{tot}}$ [fb]	δ_{EW} [%]	σ^{sig} (LO/NLO)
250	225.59(1)	206.77(1)	225.60(1)	207.0(1)	−8.25	0.4/2.1
500	53.74(1)	62.42(1)	53.74(3)	62.41(2)	+16.14	0.2/0.3
1000	12.05(1)	14.56(1)	12.0549(6)	14.57(1)	+20.84	0.5/0.5

Differential NLO fixed-order distributions

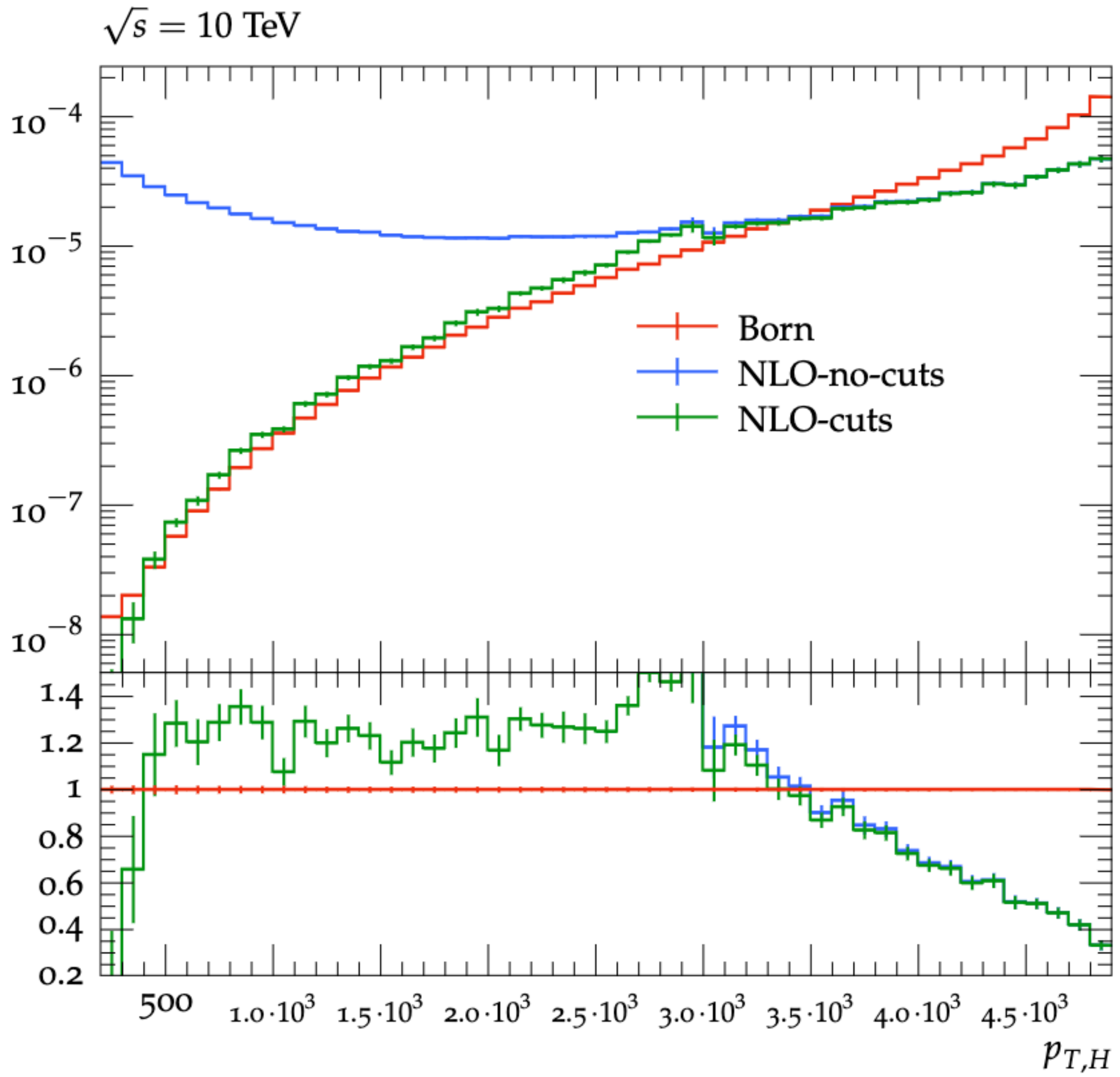
ee @ 1 TeV, NLO QCD



pp @ 13 TeV, NLO QCD



μμ @ 10 TeV, NLO EW

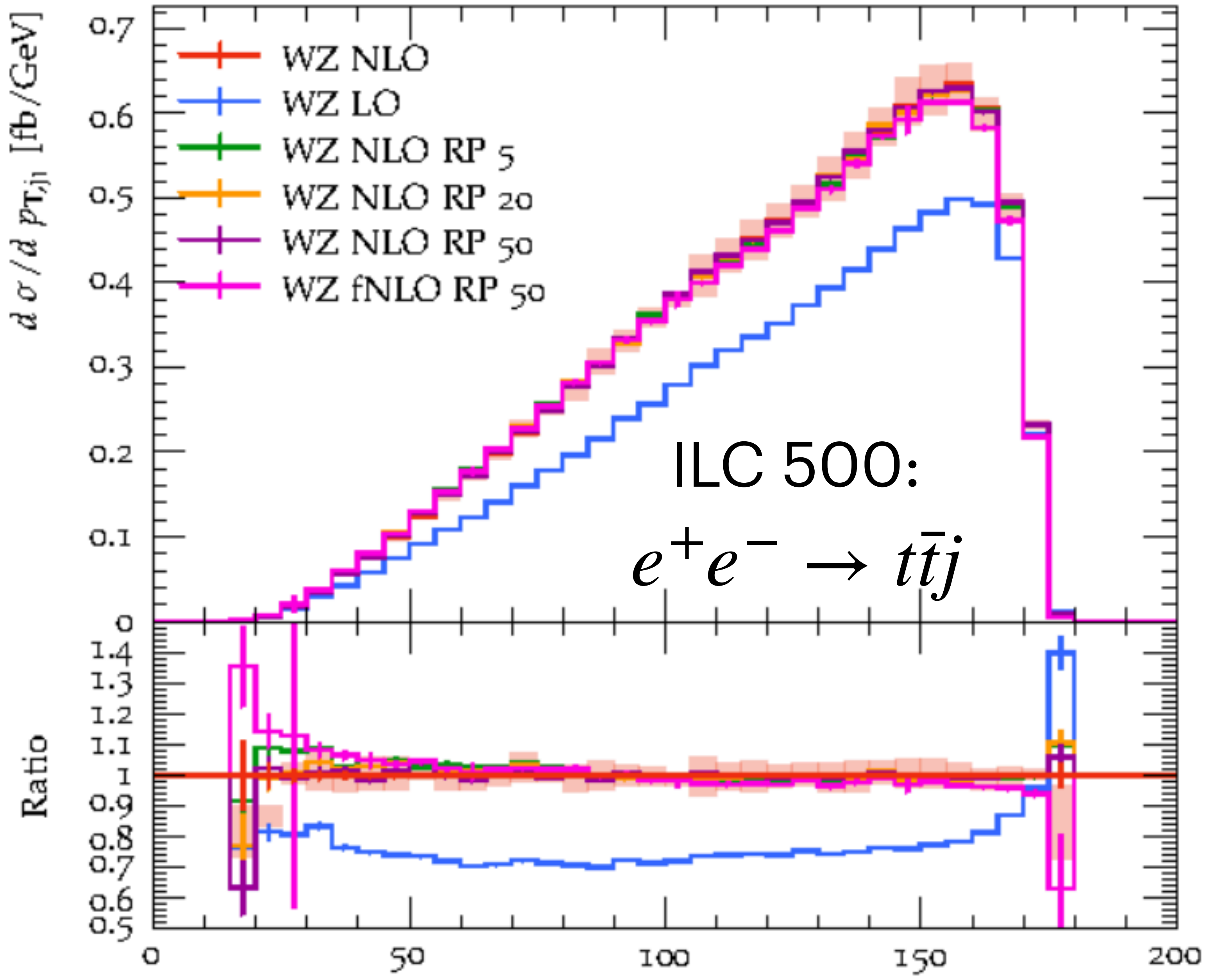


tricky numerics of eikonal terms at high energies!

arXiv: 2208.09438

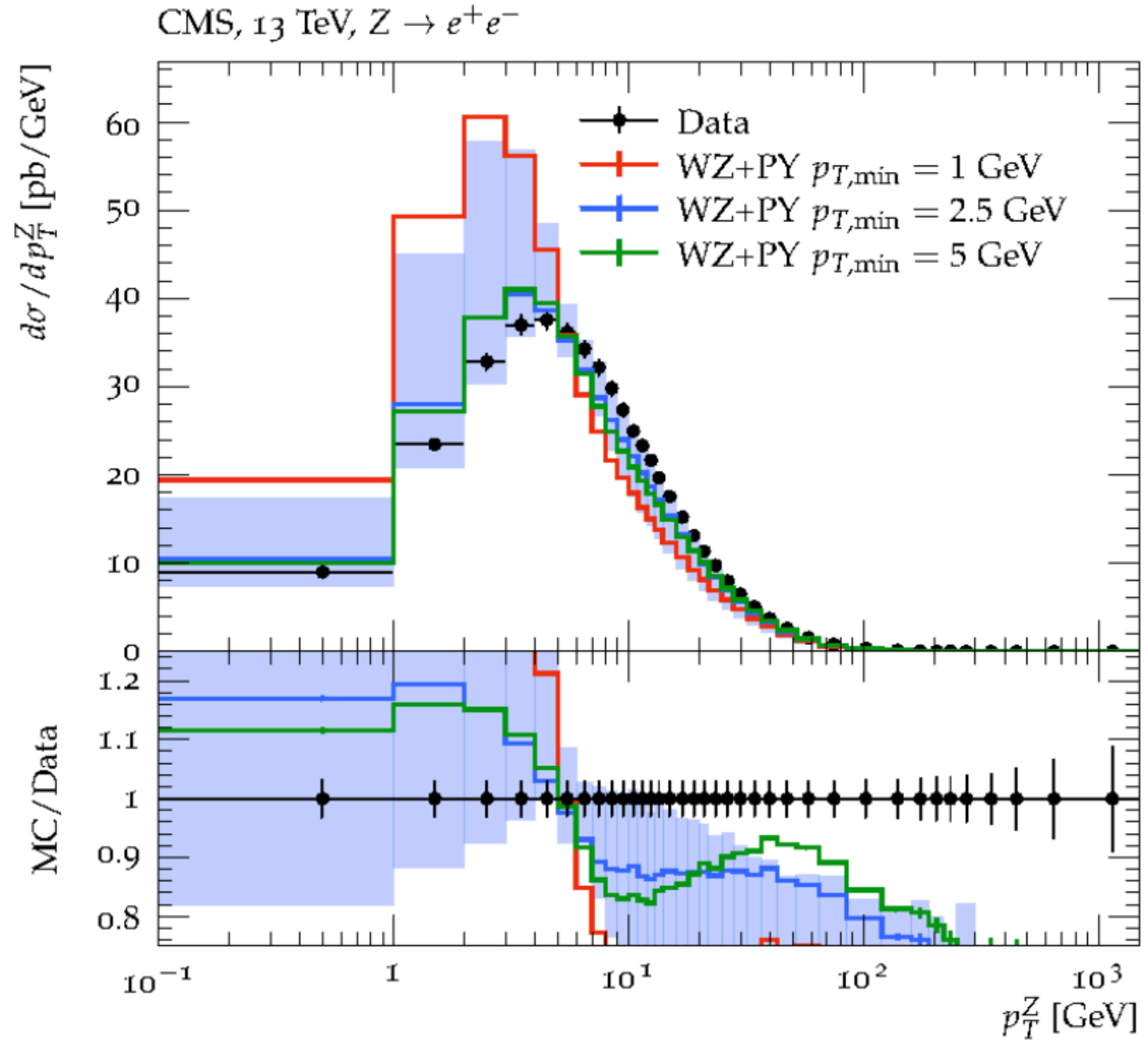
NLO POWHEG-type matching

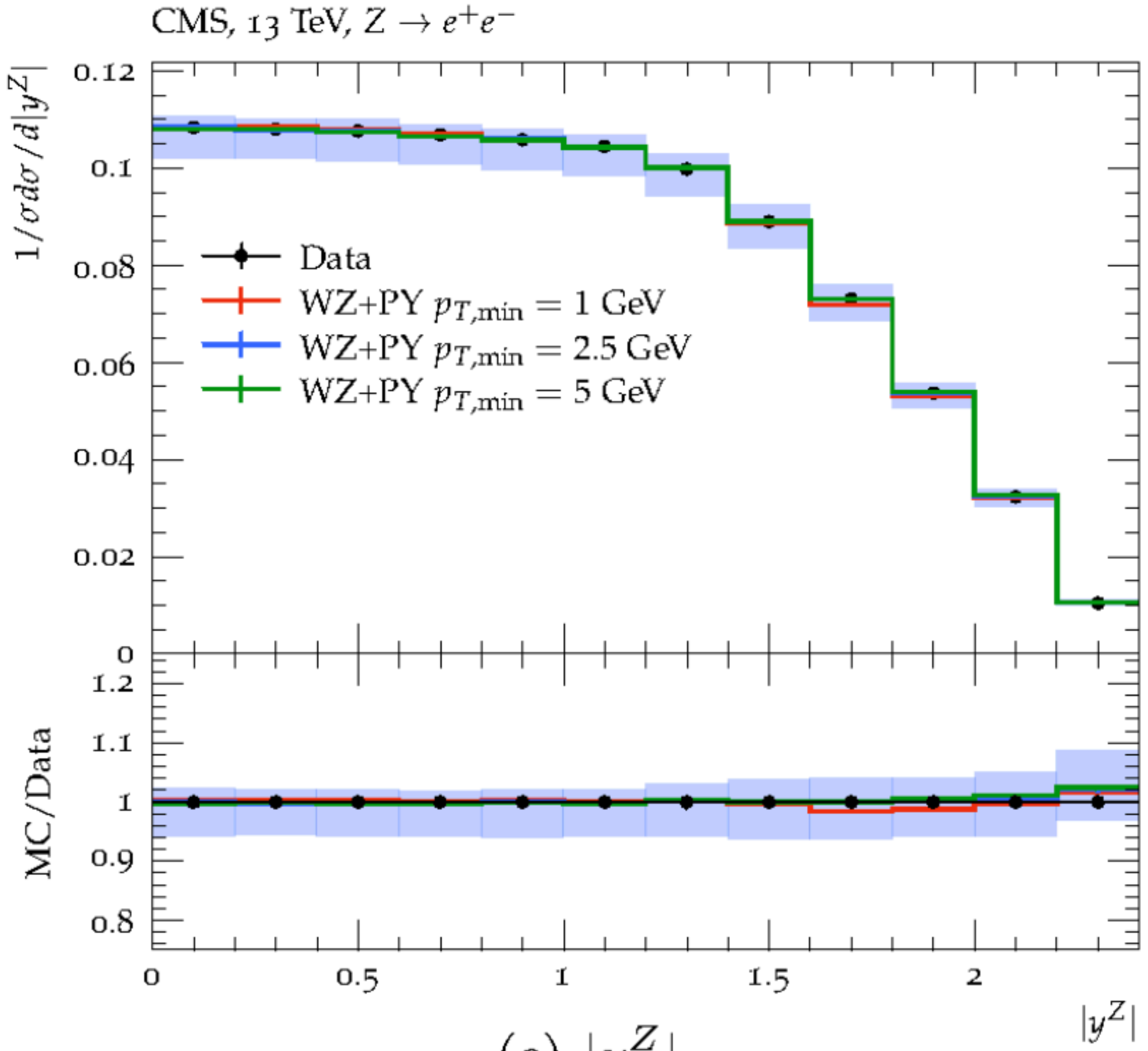
- Matching NLO real emission from hard ME and parton shower (PS)
- POWHEG method: hardest emission first [Frixione/Nason et al.]
- Process-independent NLO matching in WHIZARD



$\mu_R = {}^{H_T}/_2 \quad \text{with} \quad H_T := \sum_i \sqrt{p_{T,i}^2 + m_i^2}$

LHC 13 TeV: NC Drell-Yan $pp \to \ell^+\ell^-$ compared to CMS data



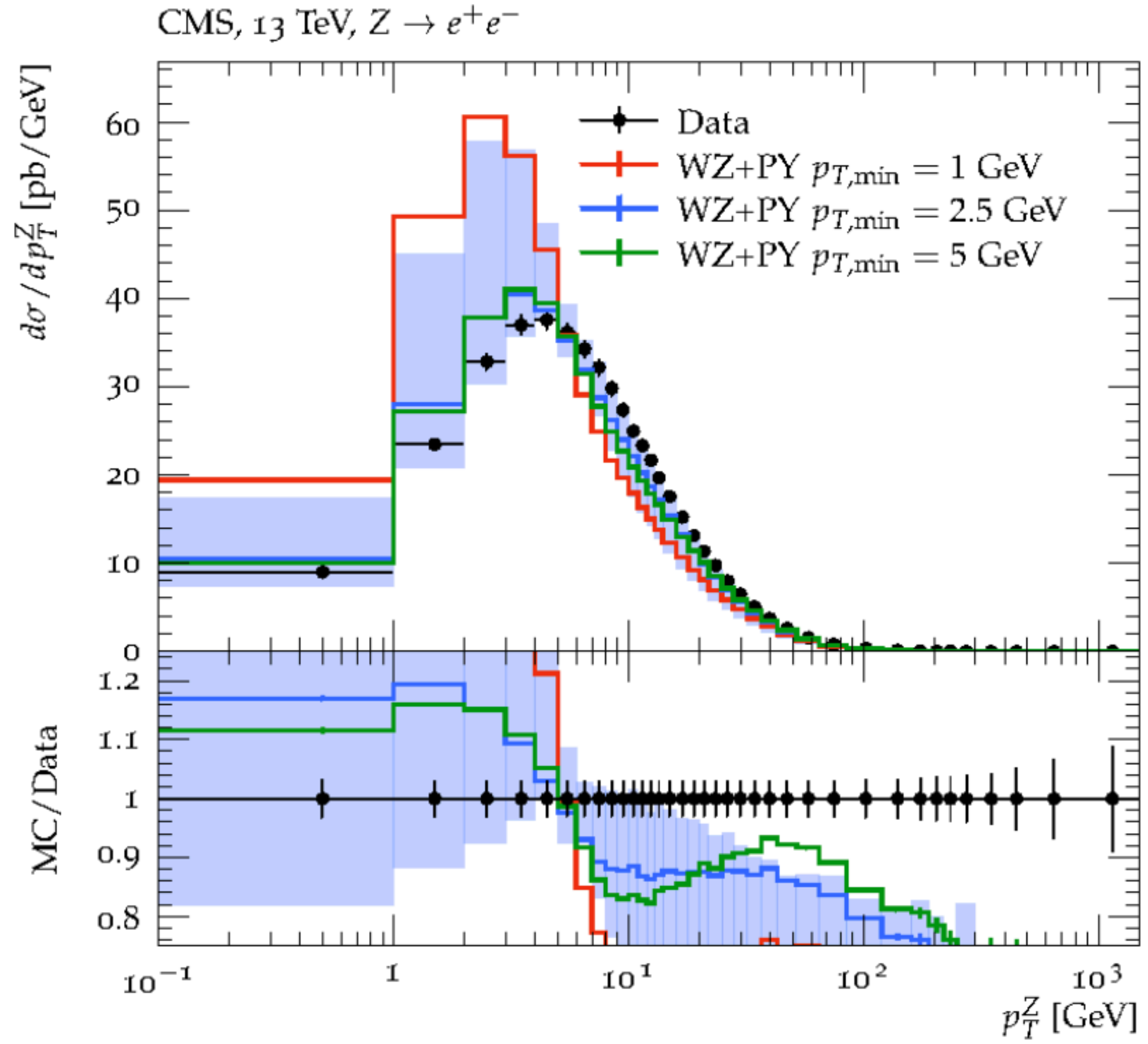


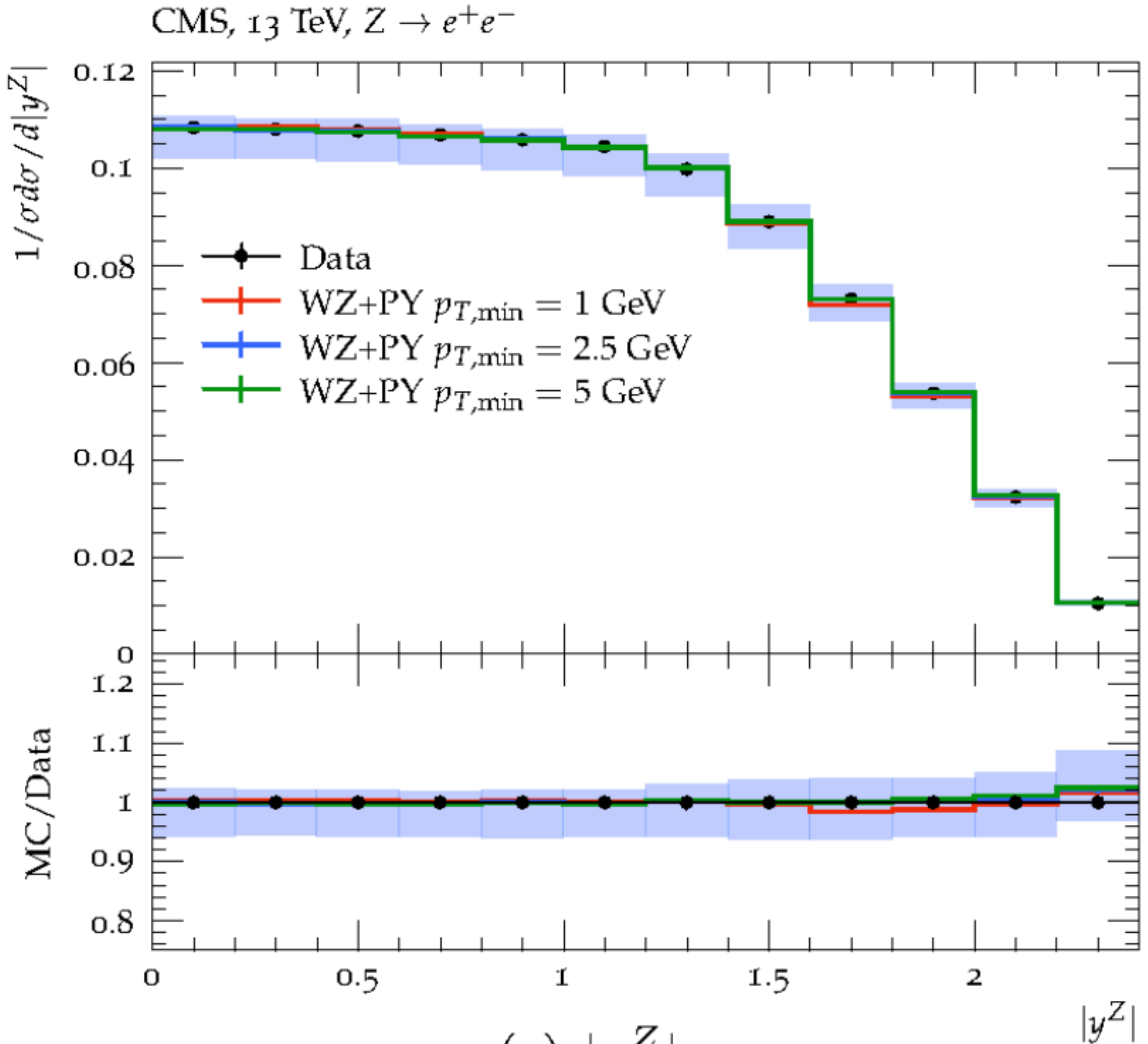
(c) $|y^Z|$

NLO POWHEG-type matching

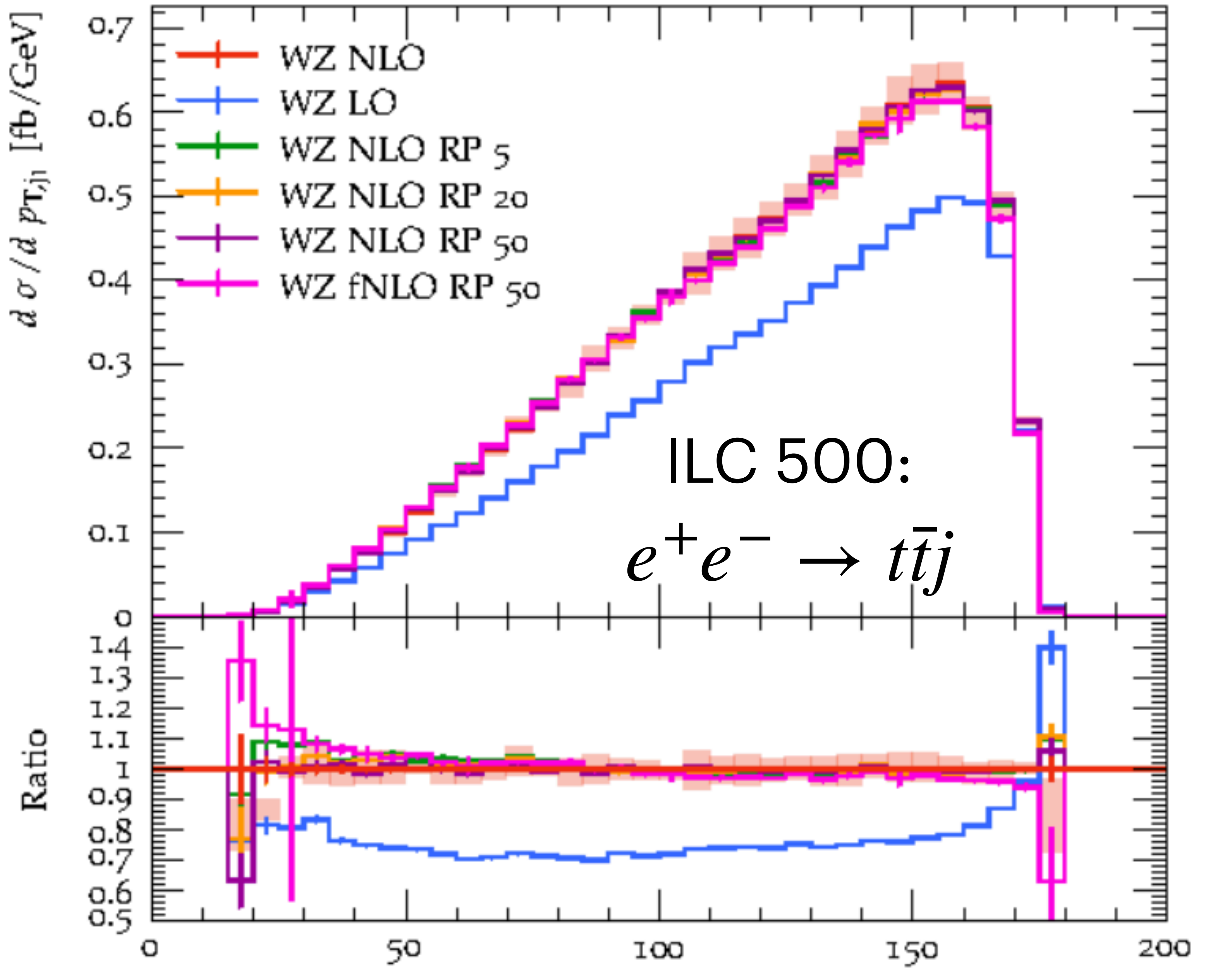
- Matching NLO real emission from hard ME and parton shower (PS)
- POWHEG method: hardest emission first [Frixione/Nason et al.]
- Process-independent NLO matching in WHIZARD

LHC 13 TeV: NC Drell-Yan $pp \to \ell^+\ell^-$ compared to CMS data





(c) $|y^Z|$

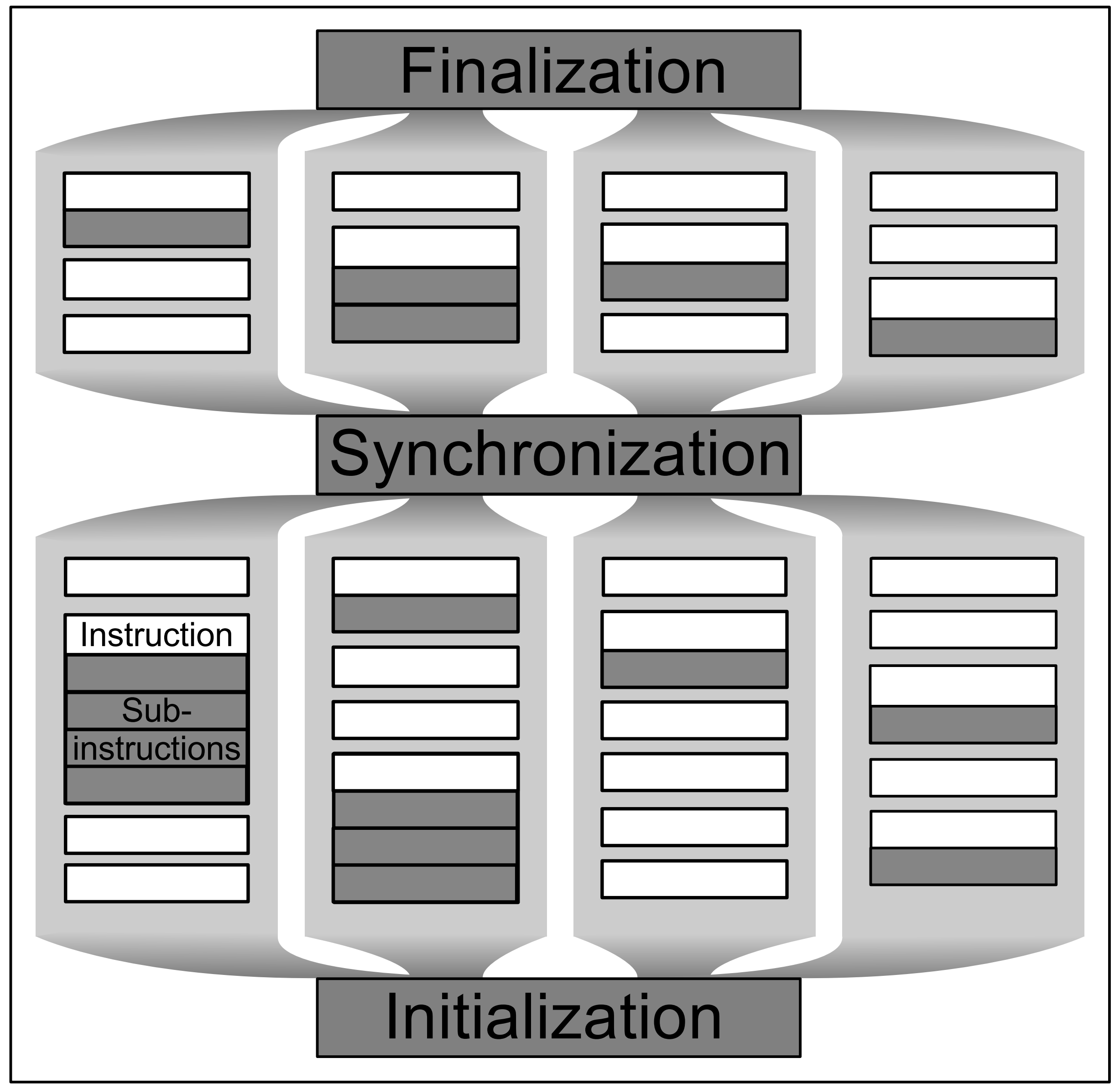


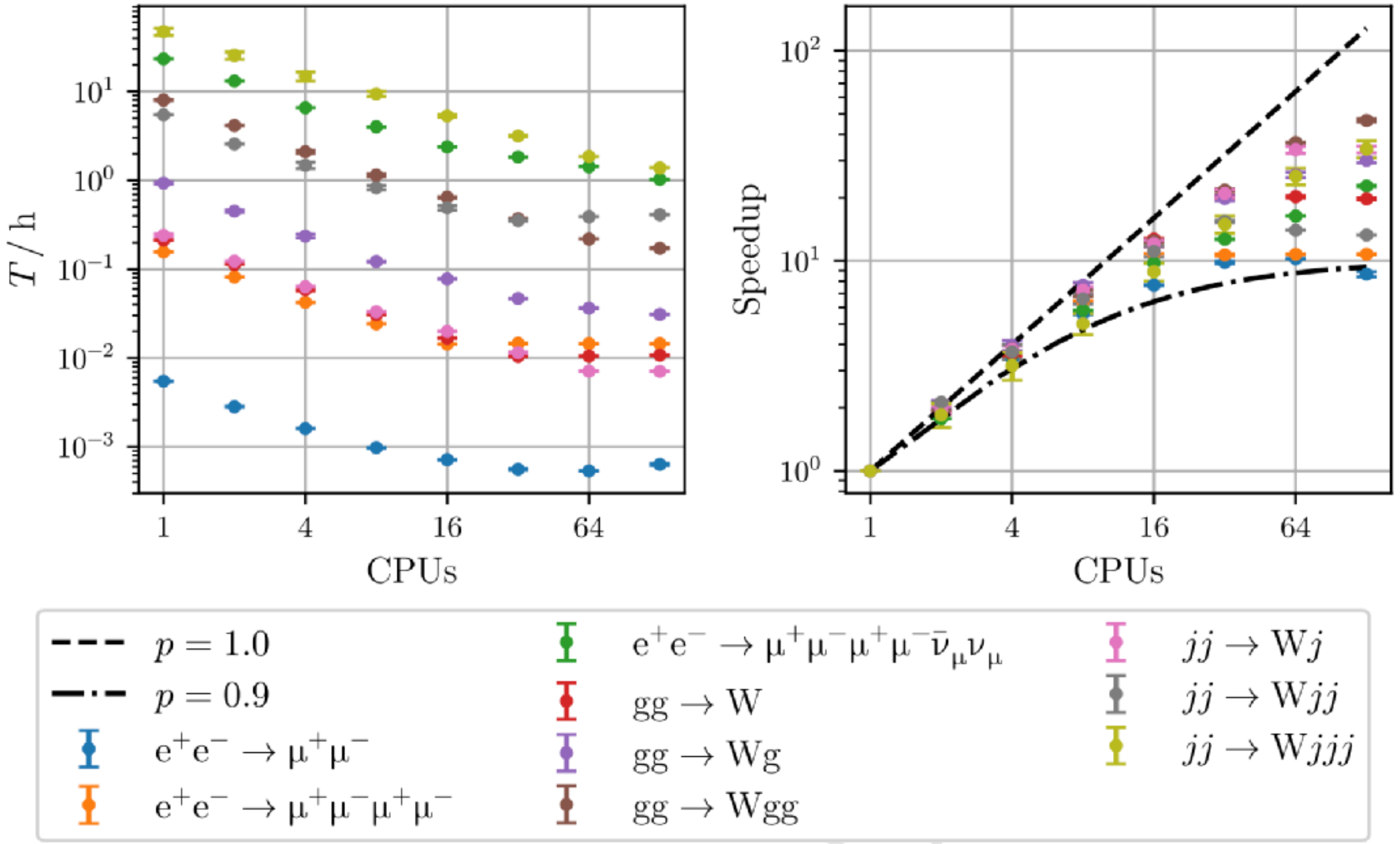
$$\mu_R = H_T/2 \quad \text{with} \quad H_T := \sum_i \sqrt{p_{T,i}^2 + m_i^2}$$

Available: all infrastructure for NLO QED/EW matching, needs to be completed/validated

Whizard in parallel

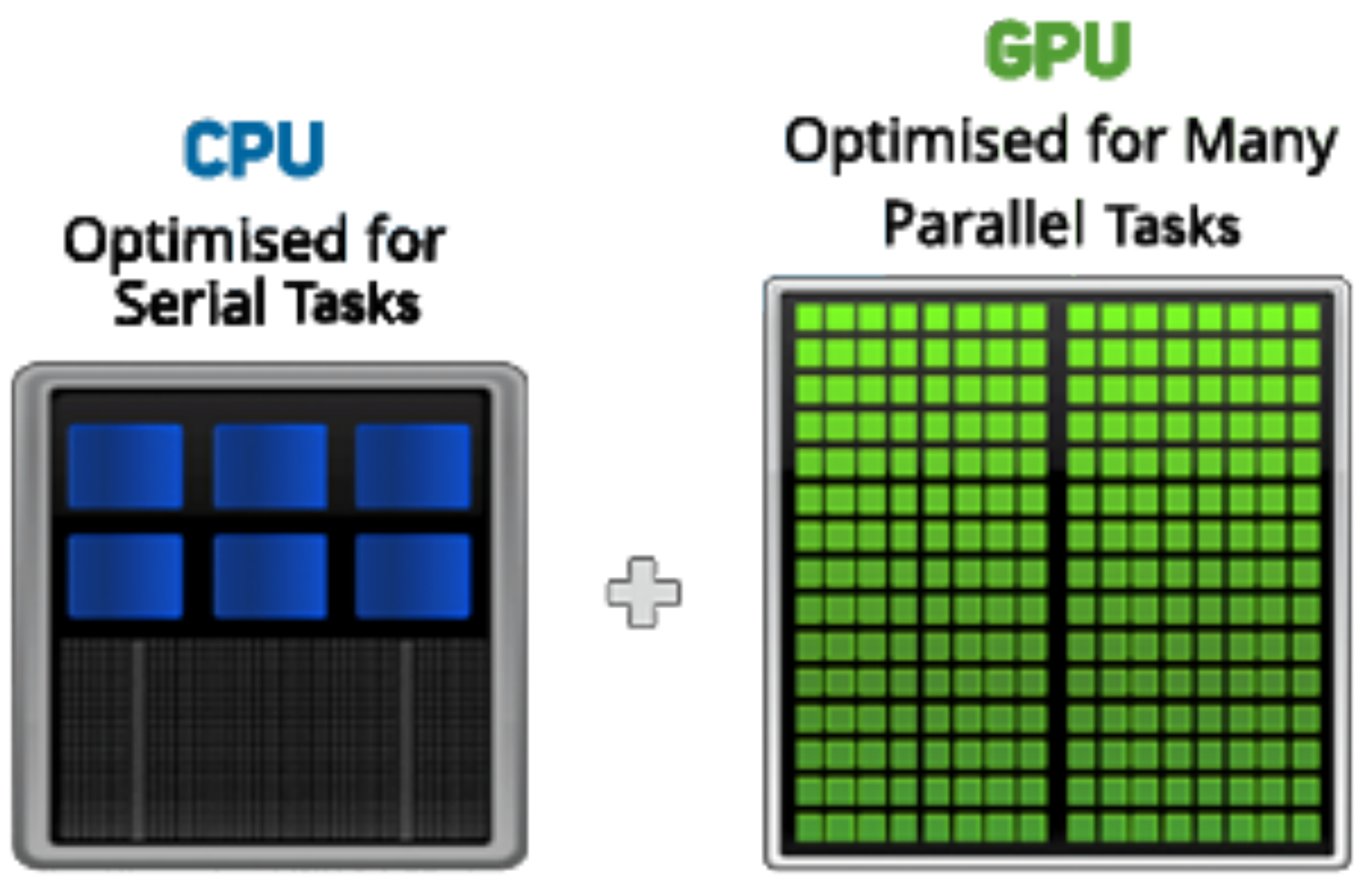
Braß/Kilian/JRR, arXiv:1811.09711





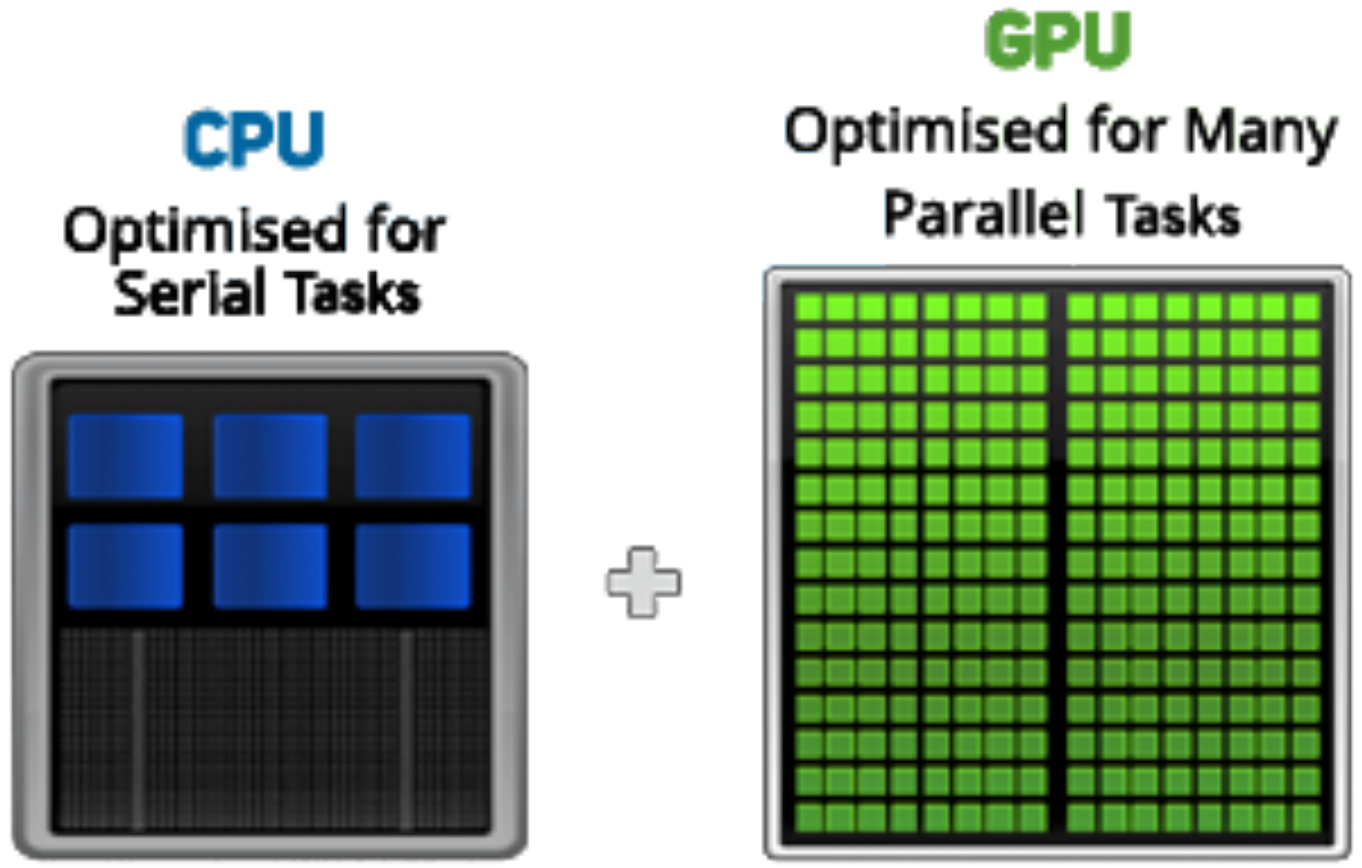
- Parallelization of integration: OMP multi-threading for different helicities
- MPI parallelization (using OpenMPI or MPICH)
- Distributes workers over multiple cores, grid adaption needs non-trivial communication
- Speedups of 20 to 50, saturation at O(100) tasks [can do also parallel event generation]
- Load balancer / non-blocking communication [v3.0.0]

Whizard on GPUs



- Joint project with former Phd student; now works for NEC supercomputers
- Main core serial (or MPI-parallel) on CPU,
- 1. step: matrix elements as libraries off-loaded to GPU
- (Semi-) automatized ME generator exists for amplitudes on GPU
- Moderate speed-ups can be seen for more complicated processes
- 2. step: phase-space generation (SIMD paradigm) on the GPU
- *W.i.p.:* phase-space adaption on the GPU (w/ minimal data transfer CPU $\longleftrightarrow$ GPU)

Whizard on GPUs

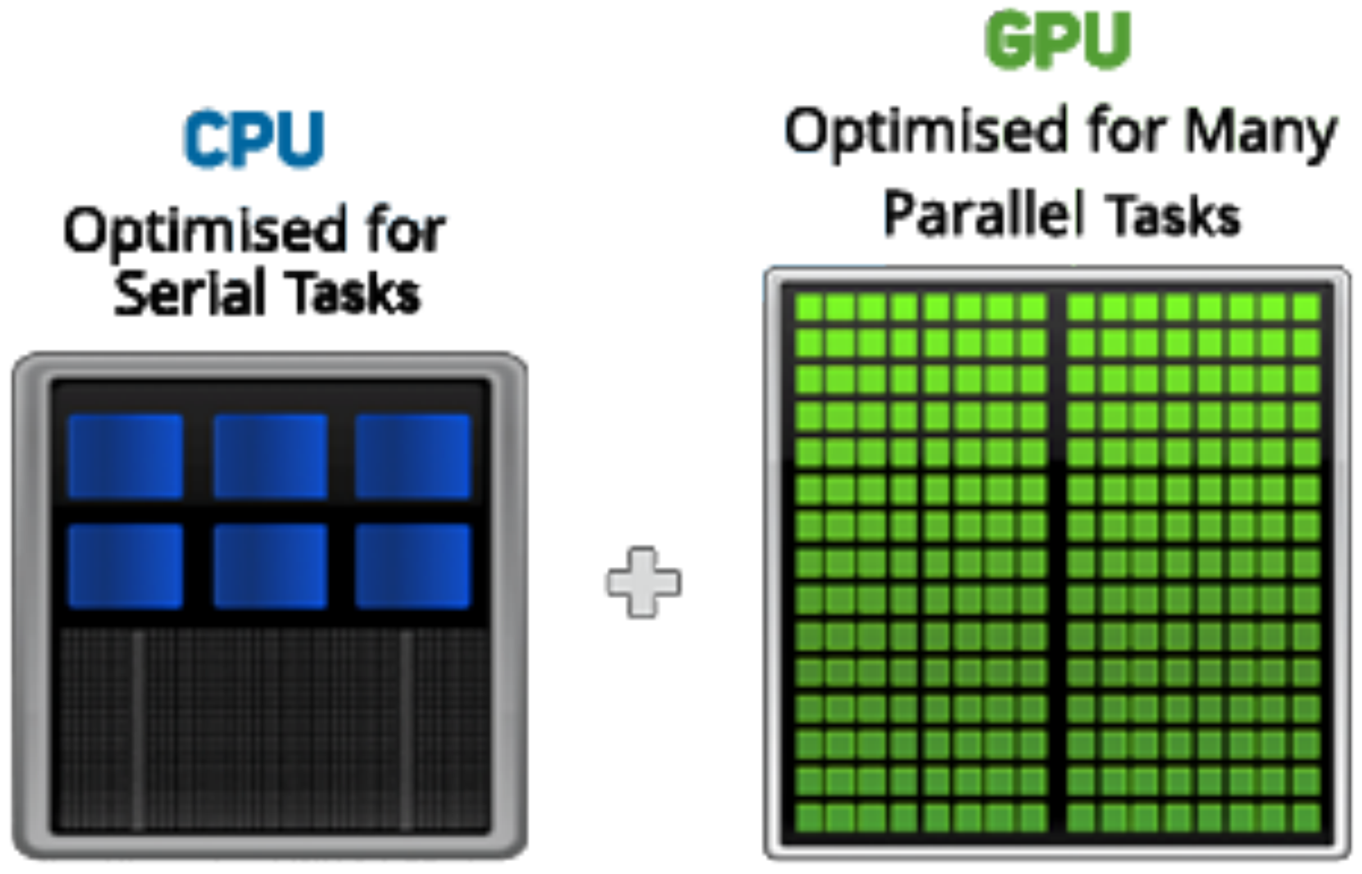


- Joint project with former Phd student; now works for NEC supercomputers
- Main core serial (or MPI-parallel) on CPU,
- 1. step: matrix elements as libraries off-loaded to GPU
- (Semi-) automatized ME generator exists for amplitudes on GPU
- Moderate speed-ups can be seen for more complicated processes
- 2. step: phase-space generation (SIMD paradigm) on the GPU
- *W.i.p.:* phase-space adaption on the GPU (w/ minimal data transfer CPU $\longleftrightarrow$ GPU)

Preliminary:

Process	$t^{CPU}[s]$	$t^{GPU}[s]$
$e^+e^- \to t\bar{t}$	0.98	4.28
$e^+e^- \to bW^+\bar{b}W^-$	28.8	23.1
$e^+e^- \to bW^+\bar{b}W^-H$	57.5	37.8
$e^+e^- \to b\bar{b}\bar{\nu}_e e^-\bar{\nu}_\mu\mu^+$	154	124
$e^+e^- \to 2j$	1.9	5.4
$e^+e^- \to 3j$	45	65
$e^+e^- \to 4j$	870	608
$e^+e^- \to 5j$	4106	978
$pp \to jj$	42	86
$pp \to W^+W^-W^+W^-$	670	192

Whizard on GPUs



- Joint project with former Phd student; now works for NEC supercomputers
- Main core serial (or MPI-parallel) on CPU,
- 1. step: matrix elements as libraries off-loaded to GPU
- (Semi-) automatized ME generator exists for amplitudes on GPU
- Moderate speed-ups can be seen for more complicated processes
- 2. step: phase-space generation (SIMD paradigm) on the GPU
- *W.i.p.:* phase-space adaption on the GPU (w/ minimal data transfer CPU $\longleftrightarrow$ GPU)

Preliminary:

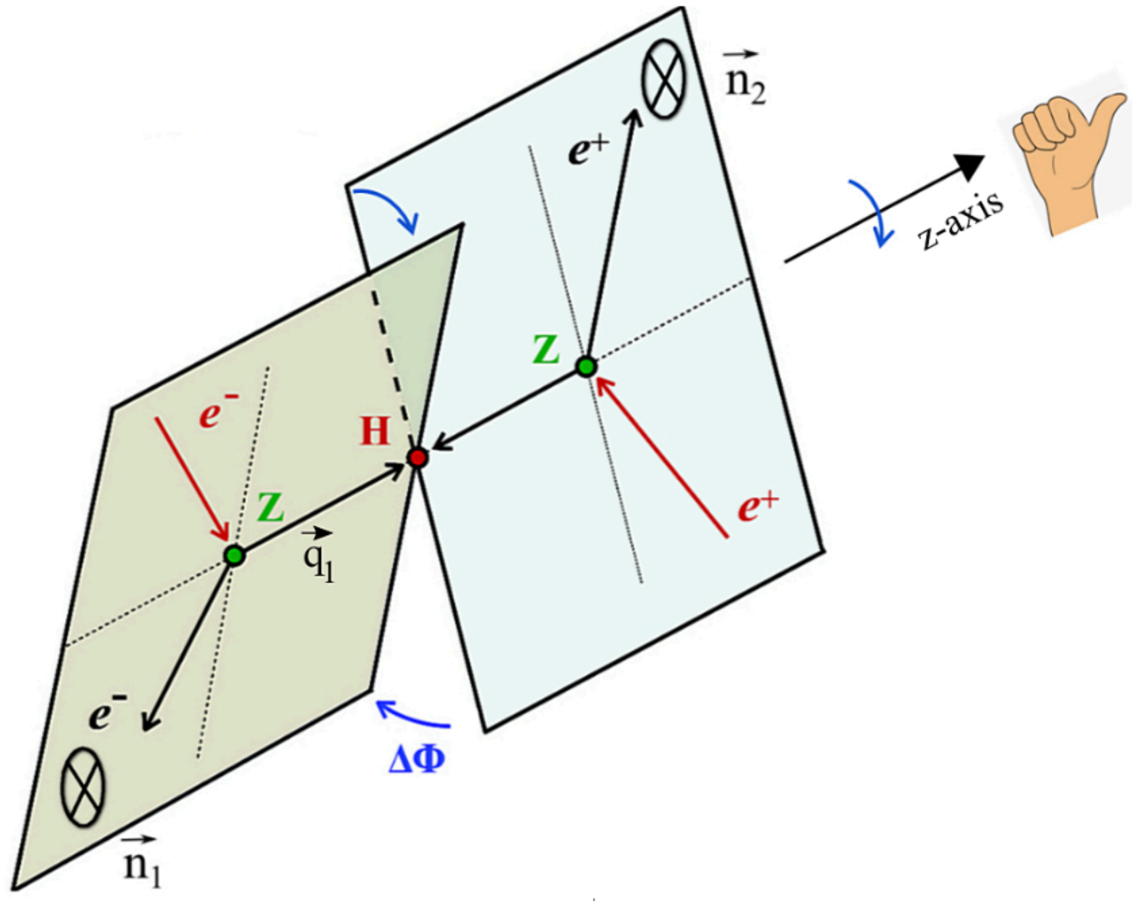
Process	$t^{CPU}[s]$	$t^{GPU}[s]$
$e^+e^- \to t\bar{t}$	0.98	4.28
$e^+e^- \to bW^+\bar{b}W^-$	28.8	23.1
$e^+e^- \to bW^+\bar{b}W^-H$	57.5	37.8
$e^+e^- \to b\bar{b}\bar{\nu}_e e^- \bar{\nu}_\mu \mu^+$	154	124
$e^+e^- \to 2j$	1.9	5.4
$e^+e^- \to 3j$	45	65
$e^+e^- \to 4j$	870	608
$e^+e^- \to 5j$	4106	978
$pp \to jj$	42	86
$pp \to W^+W^-W^+W^-$	670	192

Whizard MC Integrators:

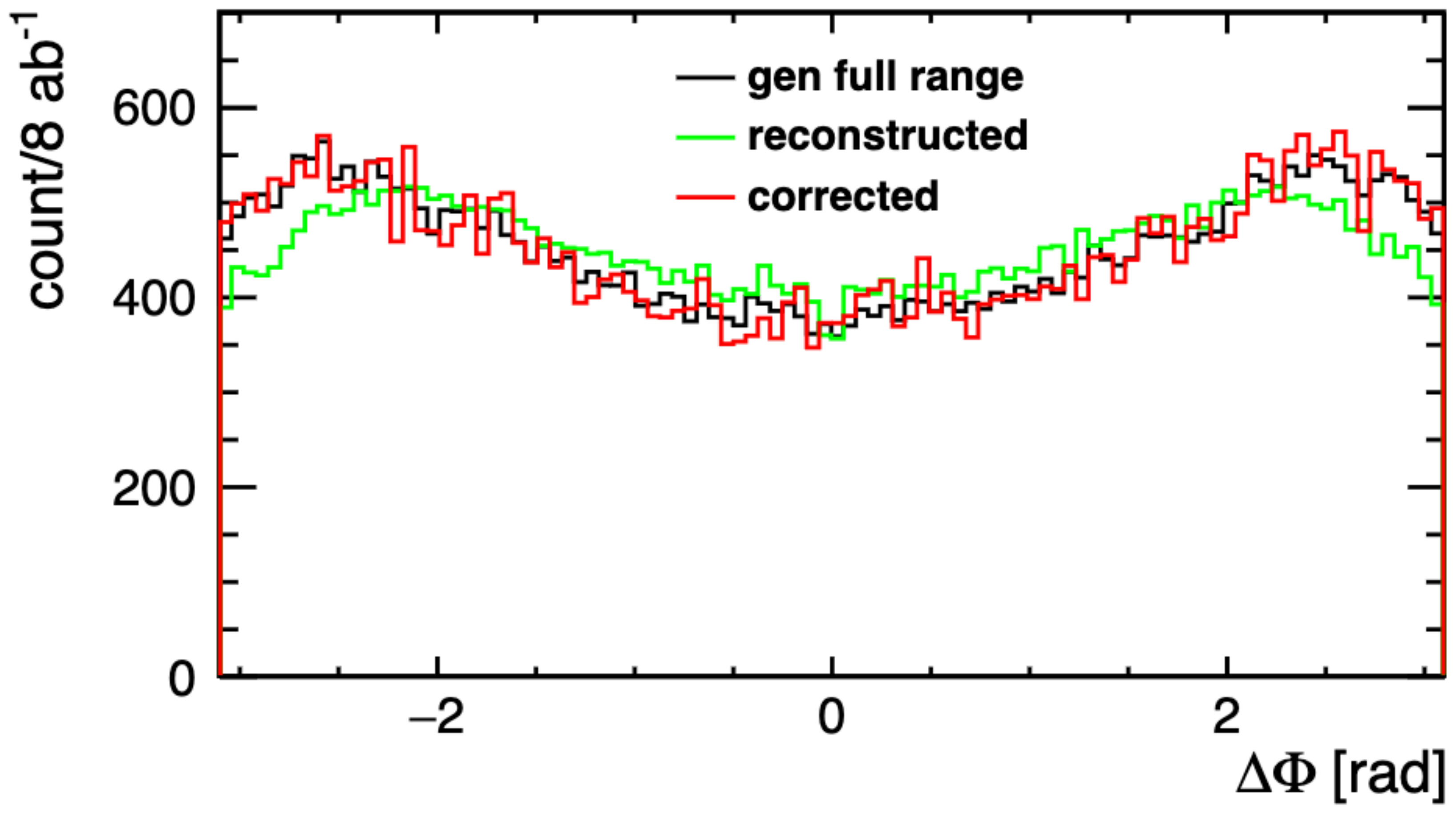
- VAMP: adaptive multi-channel Monte Carlo integrator
- VAMP2: fully MPI-parallelized version, using RNG stream generator
- [VGPU: VAMP implementation on GPU]
- [VXInt: new adaptive generator + integrator based on INNs]
  - (w.i.p first as a stand-alone tool)

News on the UFO / BSM in WHIZARD


```
model = SM  (ufo)
model = SM  (ufo ("<my UFO path>"))
```



- ☑ WHIZARD 2.8.3: Full UFO (1) support
- ☑ Fermion-number violating interactions (3.0.0)
- ☑ (N)LO matrix elements from UFO models (particularly SMEFTSim v3.x)
- ☑ Arbitrary Lorentz structures supported
- ☑ 5-, 6-, 7-, 8-, ... point vertices (optimization for code generation pending)
- ☑ Customized propators; Spin 0, 1/2, 1, 3/2, 2 ; BSM SLHA input (2.8.3,3.2.x)
- ☑ Lots of bug reports and constructive feedback from many different users



New paper on UFO 2.0: Darmé et al. arXiv: 2304.09883

I. Bozović-Jelizavčić, 2405.05820

New features, ongoing development

BSM @ NLO (QCD) with UFO

- GoSam was the first OLP that kicked off NLO automation in Whizard in 2013
- Revived 2023 with NLO QCD for BSM models (e.g. SMEFT) for LHC   J. Braun/P. Bredt/G. Heinrich/M. Höfer/JRR
  - End of 2023: full validation of NLO QCD processes for LHC within SM: $pp \to t\bar{t}, pp \to t\bar{t}H, pp \to \gamma\gamma, pp \to \gamma j \ldots.$
- Full support for Whizard⊕GoSam for MPI (Message Passing Interface) parallelization
- GoSam UFO NLO interface allows support for almost any model
- W.i.p.: Note yet supported neither by the public Whizard nor GoSam versions
- Implementation and validation of resonance-aware subtraction for pp processes in Whizard
- 2024: First test runs for NLO QCD corrections for UFO BSM models

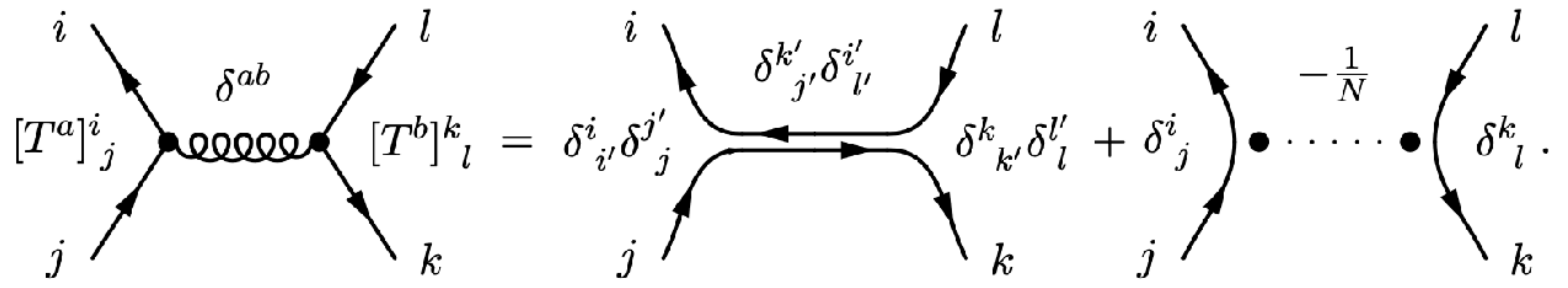
```
+--------------------------------------------------------------------+
|  __   __   ___   __   __ __                  GoSam                 |
| / _) /  \ / __) (  ) (  \/  )         An Automated One-Loop        |
| ( (/\( () )\__ \ /__\  )    (        Matrix Element Generator      |
| \__/ \__/ (___/(_)(_)(_/\/\_)        Version 2.1.0 Rev: 93fd8c5    |
|                                                                    |
|                            (c) The GoSam Collaboration 2011-2021   |
|                                                                    |
|          AUTHORS:                                                  |
|          * Gudrun Heinrich      <gudrun@mpp.mpg.de>                |
|          * Stephen Jones        <s.jones@cern.ch>                  |
|          * Matthias Kerner      <mkerner@physik.uzh.ch>            |
|          * Vitaly Magerya       <vitaly.magerya@tx97.net>          |
|          * Pierpaolo Mastrolia  <Pierpaolo.Mastrolia@cern.ch>      |
|          * Giovanni Ossola      <gossola@citytech.cuny.edu>        |
|          * Tiziano Peraro       <peraro@mpp.mpg.de>                |
|          * Johannes Schlenk     <johannes.schlenk@psi.ch>          |
|          * Francesco Tramontano <Francesco.Tramontano@cern.ch>     |
|                                                                    |
|          FORMER AUTHORS:                                           |
|          * Gavin Cullen         <gavin.cullen@desy.de>             |
|          * Hans van Deurzen     <hdeurzen@mpp.mpg.de>              |
|          * Nicolas Greiner      <greiner@mpp.mpg.de>               |
|          * Stephan Jahn         <sjahn@mpp.mpg.de>                 |
|          * Gionata Luisoni      <luisonig@mpp.mpg.de>              |
|          * Edoardo Mirabella    <mirabell@mpp.mpg.de>              |
|          * Joscha Reichel       <joscha@mpp.mpg.de>                |
|          * Thomas Reiter        <reiterth@mpp.mpg.de>              |
|          * Johann Felix von Soden-Fraunhofen <jfsoden@mpp.mpg.de>  |
|                                                                    |
|  This program is free software: you can redistribute it and/or modify |
|  it under the terms of the GNU General Public License either       |
|  version 3, or (at your option) any later version.                 |
|                                                                    |
|  Scientific publications prepared using the present version of    |
|  GoSam or any modified version of it or any code linking to GoSam |
|  or parts of it should make a clear reference to the publication: |
|                                                                    |
|      G. Cullen et al.,                                             |
|      ``GoSam-2.0: a tool for automated one-loop calculations       |
|                     within the Standard Model and Beyond'',        |
|      Eur. Phys. J. C 74 (2014) 8,  3001                            |
|      [arXiv:1404.7096 [hep-ph]].                                   |
```

```
|=============================================================================
|                              WHIZARD 3.1.4.1
|=============================================================================
| Reading model file '/home/reuter/local/share/whizard/models/SM.mdl'
| Preloaded model: SM
| Process library 'default_lib': initialized
| Preloaded library: default_lib
| Reading model file '/home/reuter/local/share/whizard/models/SM_hadrons
| Reading commands from file 'gg_ttH_r.sin'
| Model: Generating model 'SM_with_ggh_UFO' from UFO sources
| Model: Searching for UFO sources in '/home/reuter/local/packages/whiza
UFO/Minimal_example'
| Model: Found UFO sources for model 'SM_with_ggh_UFO'
| Model: Model file 'SM_with_ggh_UFO.ufo.mdl' generated
| Reading model file 'SM_with_ggh_UFO.ufo.mdl'
| Switching to model 'SM_with_ggh_UFO' (generated from UFO source)
SM_with_ggh_UFO.MB =>  0.000000000000E+00
SM_with_ggh_UFO.MT =>  1.725000000000E+02
SM_with_ggh_UFO.WT =>  0.000000000000E+00
SM_with_ggh_UFO.MH =>  1.250000000000E+02
SM_with_ggh_UFO.WH =>  0.000000000000E+00
SM_with_ggh_UFO.Lambda =>  1.000000000000E+03
SM_with_ggh_UFO.CphiG =>  0.000000000000E+00
```

```
| ----------------------------------------------------------------------
| Process [scattering]: 'nlo_tt'
|   Library name  = 'default_lib'
|   Process index = 1
|   Process components:
|     1: 'nlo_tt_i1':   e+, e- => t, tbar [omega]
|     2: 'nlo_tt_i2':   e+, e- => t, tbar, gl [omega], [real]
|     3: 'nlo_tt_i3':   e+, e- => t, tbar [gosam], [virtual]
|     4: 'nlo_tt_i4':   e+, e- => t, tbar [inactive], [subtraction]
| ----------------------------------------------------------------------

     1       8192     8.813E+01   9.34E-03    0.01    0.01    45.0
     2       8192     8.812E+01   8.16E-03    0.01    0.01    76.9
|---------------------------------------------------------------------------|
     2      16384     8.813E+01   6.15E-03    0.01    0.01    76.9    0.88   2
|===========================================================================|
| Integrate: sum of all components
|===========================================================================|
| It       Calls  Integral[fb]  Error[fb]   Err[%]    Acc  Eff[%]   Chi2 N[It] |
|===========================================================================|
   1           0     5.599E+02   1.30E-01    0.02    0.00    66.9
|---------------------------------------------------------------------------|
| NLO Correction: [O(alpha_s+1)/O(alpha_s)]
|  (   2.75 +-   0.02 ) %
|===========================================================================|
| There were no errors and    2 warning(s).
| WHIZARD run finished.
|===========================================================================|
```

Color exotics in Whizard

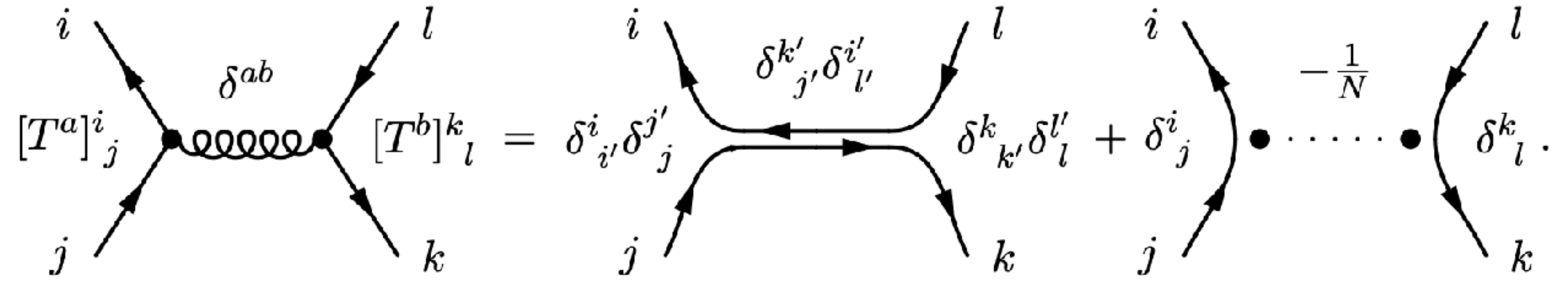
- Recent work allows to generate completely arbitrary SU(N) T. Ohl, JHEP 06 (2024) 203
- Implementation of birdtrack algorithm: allows for generic Lie groups



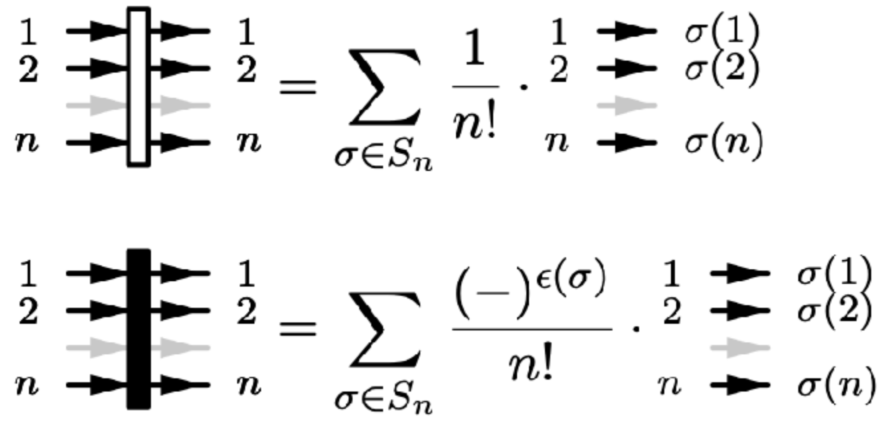
- Based on color-flow implementation in Whizard
- Very important for dim-6, dim-8, ... operators in SMEFT for e.g. Dark Sector/Dark Matter models
- Matrix element generator fully capable of completely general color exotics
- W.i.p.: support to handle this on the event generation
- Benefits for free: epsilon structures (e.g. RPV SUSY), sextets, decuplets etc.
- Comes with automated Clebsch-Gordan decomposition
- Some example vertices:

Color exotics in Whizard

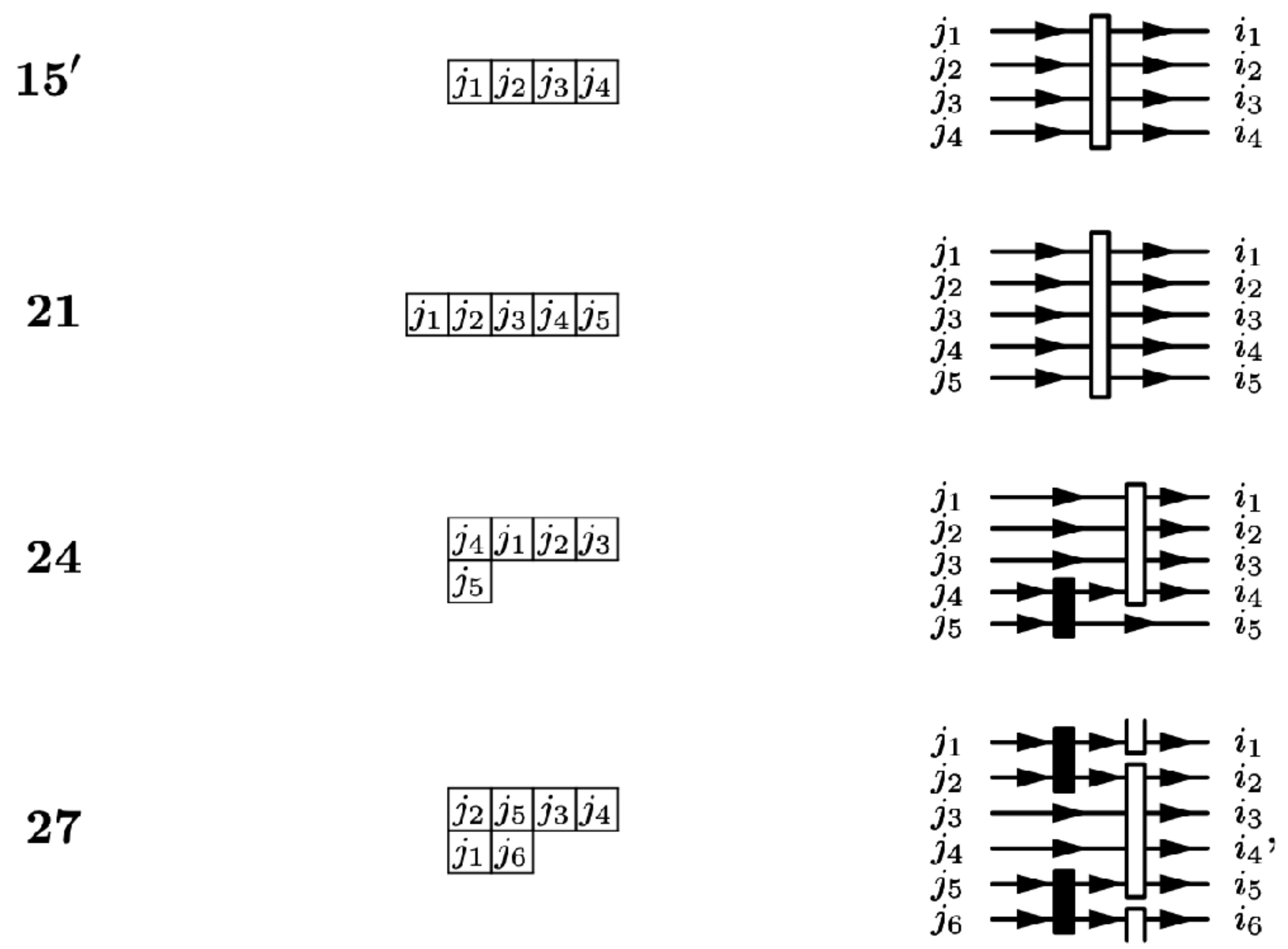
- Recent work allows to generate completely arbitrary SU(N) T. Ohl, JHEP 06 (2024) 203
- Implementation of birdtrack algorithm: allows for generic Lie groups
- Based on color-flow implementation in `Whizard`



- Very important for dim-6, dim-8, ... operators in SMEFT for e.g. Dark Sector/Dark Matter models
- Matrix element generator fully capable of completely general color exotics
- W.i.p.: support to handle this on the event generation

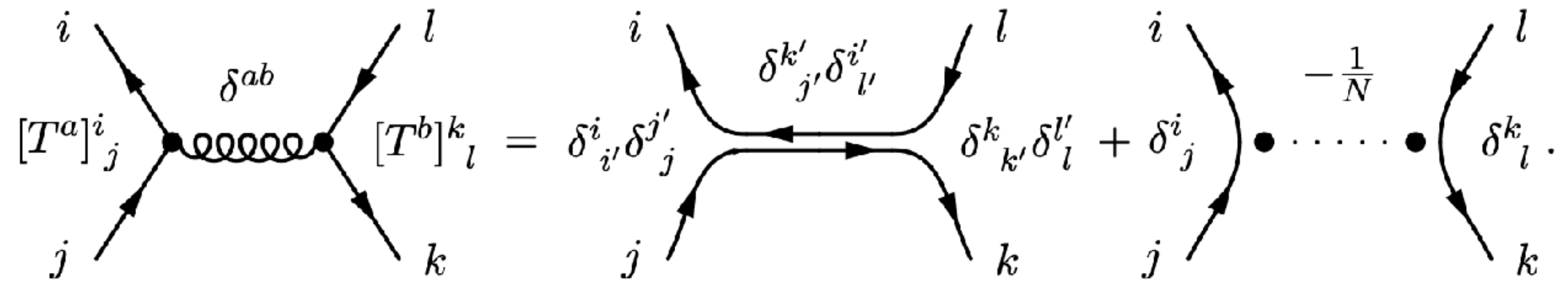


- Benefits for free: epsilon structures (e.g. RPV SUSY), sextets, decuplets etc.
- Comes with automated Clebsch-Gordan decomposition
- Some example vertices:

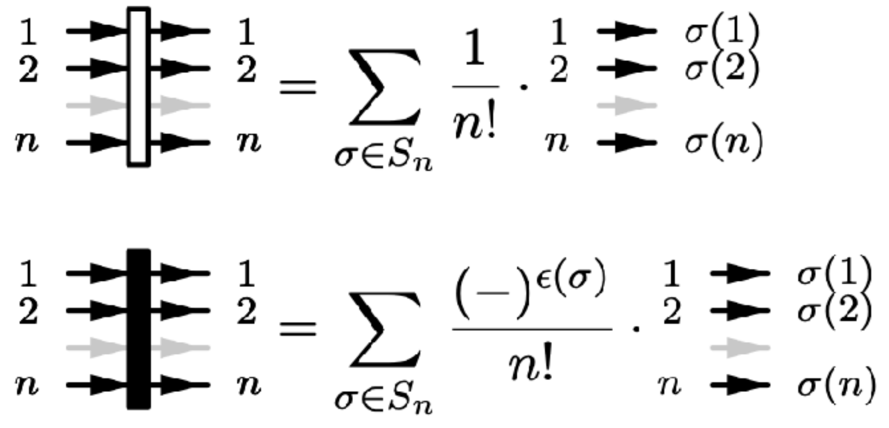


Color exotics in `Whizard`

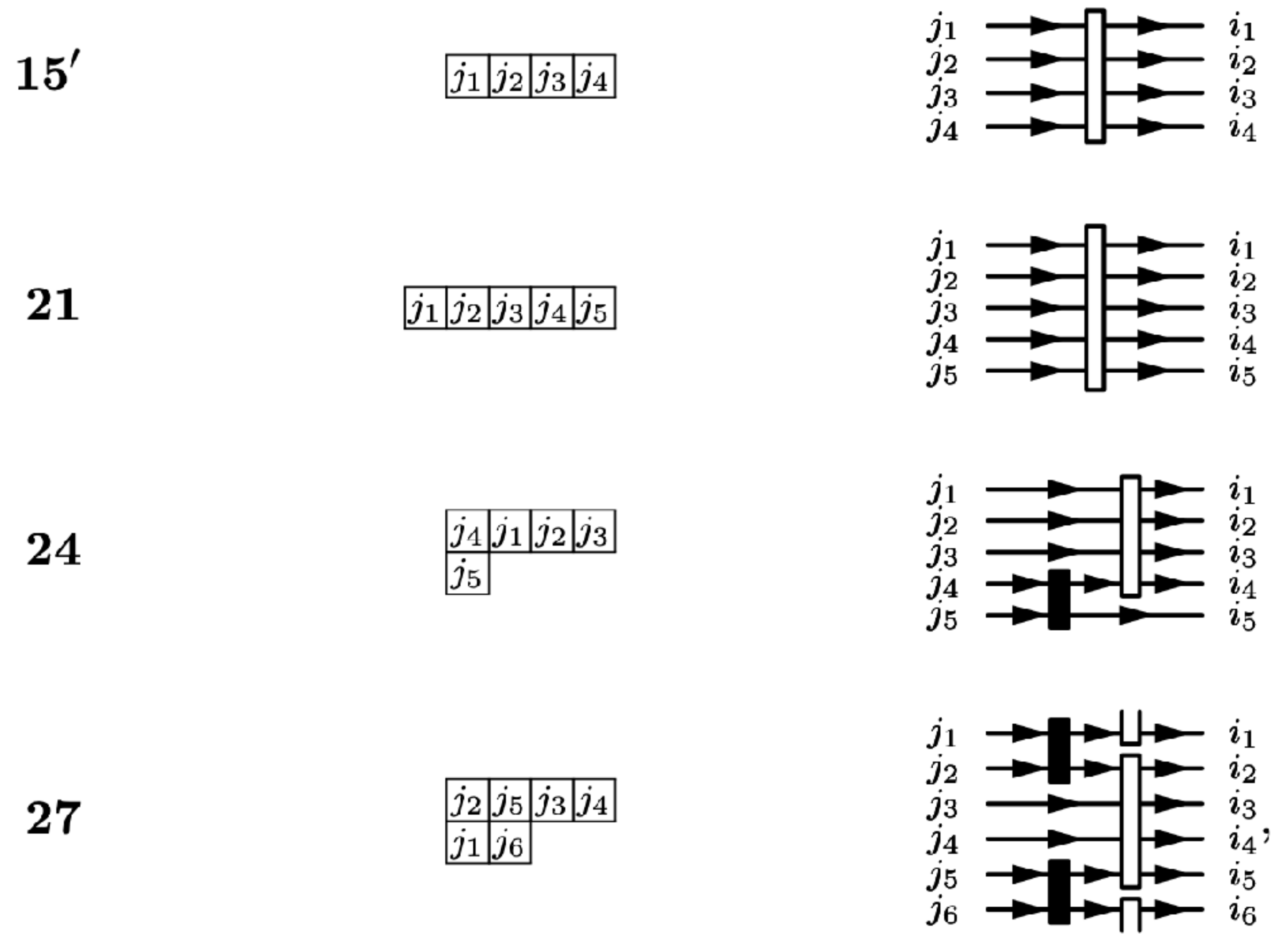
- Recent work allows to generate completely arbitrary SU(N) T. Ohl, JHEP 06 (2024) 203
- Implementation of birdtrack algorithm: allows for generic Lie groups
- Based on color-flow implementation in `Whizard`

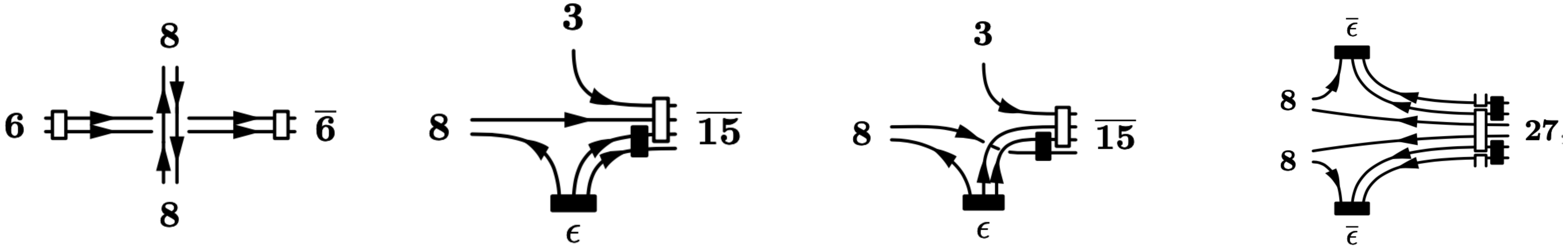


- Very important for dim-6, dim-8, ... operators in SMEFT for e.g. Dark Sector/Dark Matter models
- Matrix element generator fully capable of completely general color exotics
- W.i.p.: support to handle this on the event generation



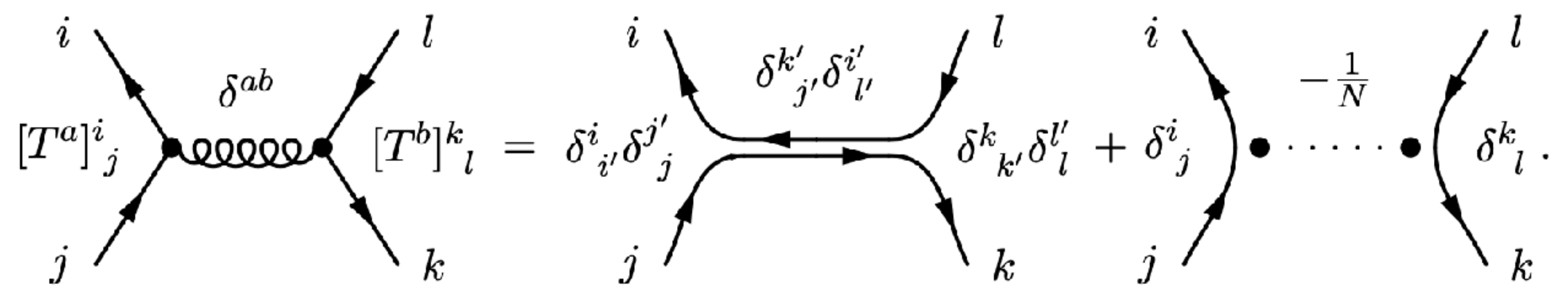
- Benefits for free: epsilon structures (e.g. RPV SUSY), sextets, decuplets etc.
- Comes with automated Clebsch-Gordan decomposition
- Some example vertices:



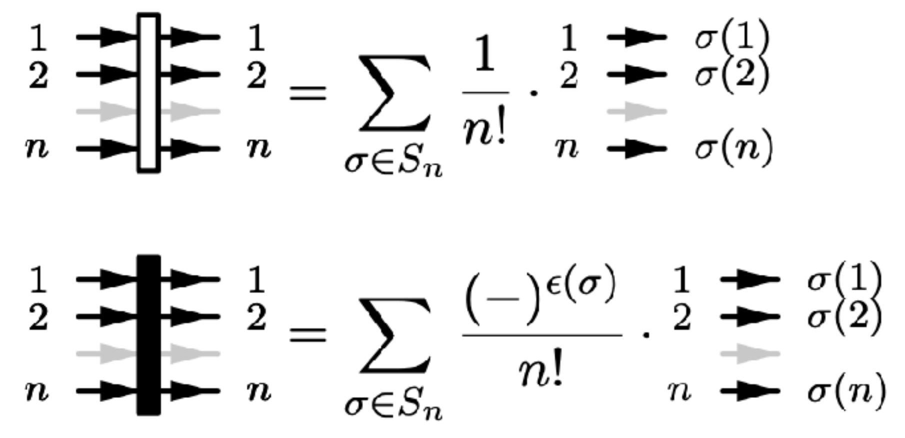


Color exotics in Whizard

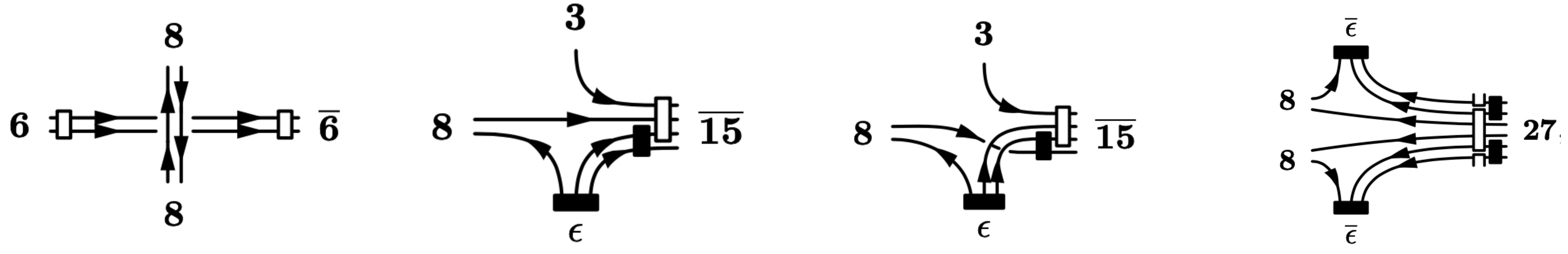
- Recent work allows to generate completely arbitrary SU(N) T. Ohl, JHEP 06 (2024) 203
- Implementation of birdtrack algorithm: allows for generic Lie groups
- Based on color-flow implementation in `Whizard`



- Very important for dim-6, dim-8, ... operators in SMEFT for e.g. Dark Sector/Dark Matter models
- Matrix element generator fully capable of completely general color exotics
- W.i.p.: support to handle this on the event generation



- Benefits for free: epsilon structures (e.g. RPV SUSY), sextets, decuplets etc.
- Comes with automated Clebsch-Gordan decomposition
- Some example vertices:

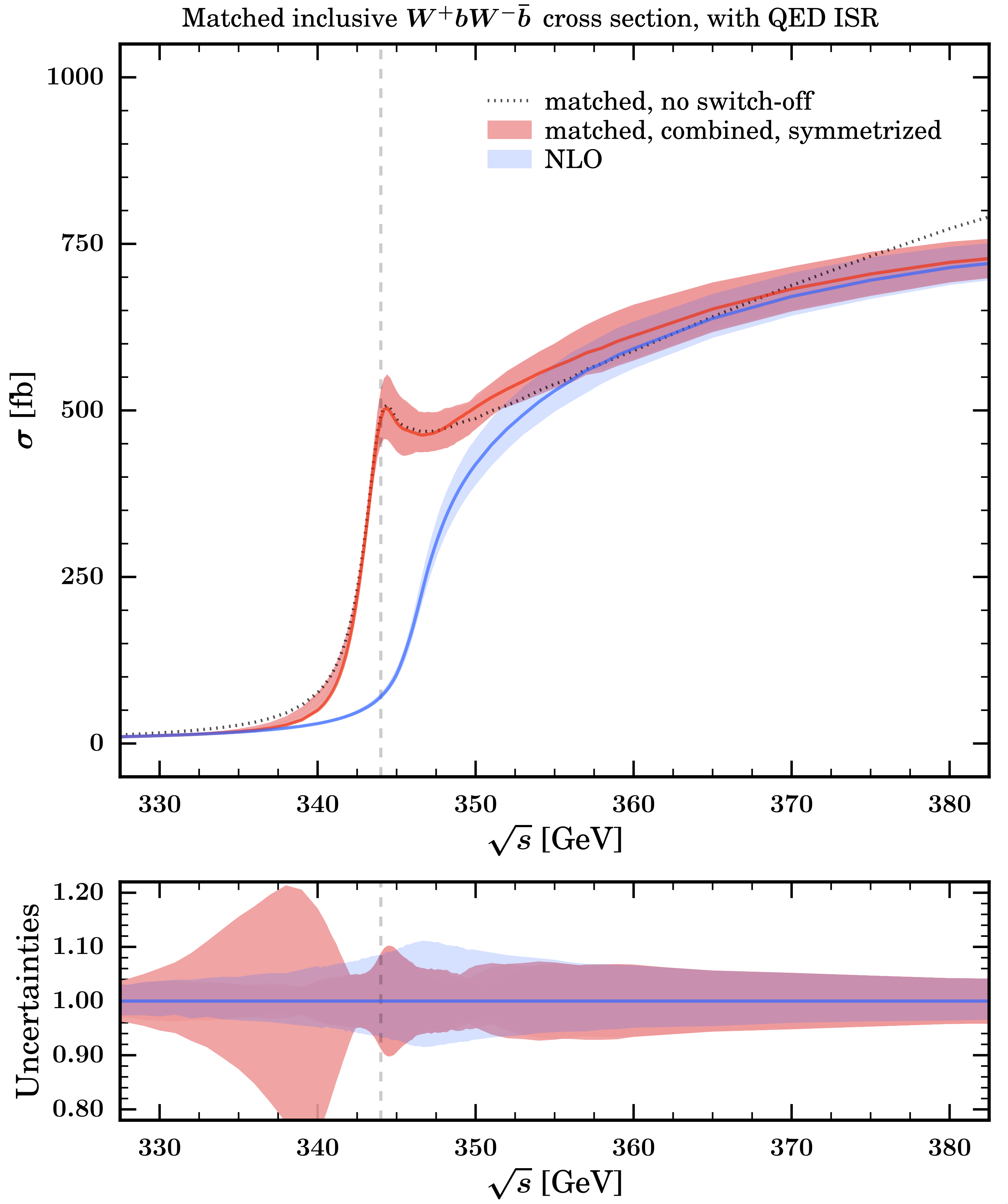


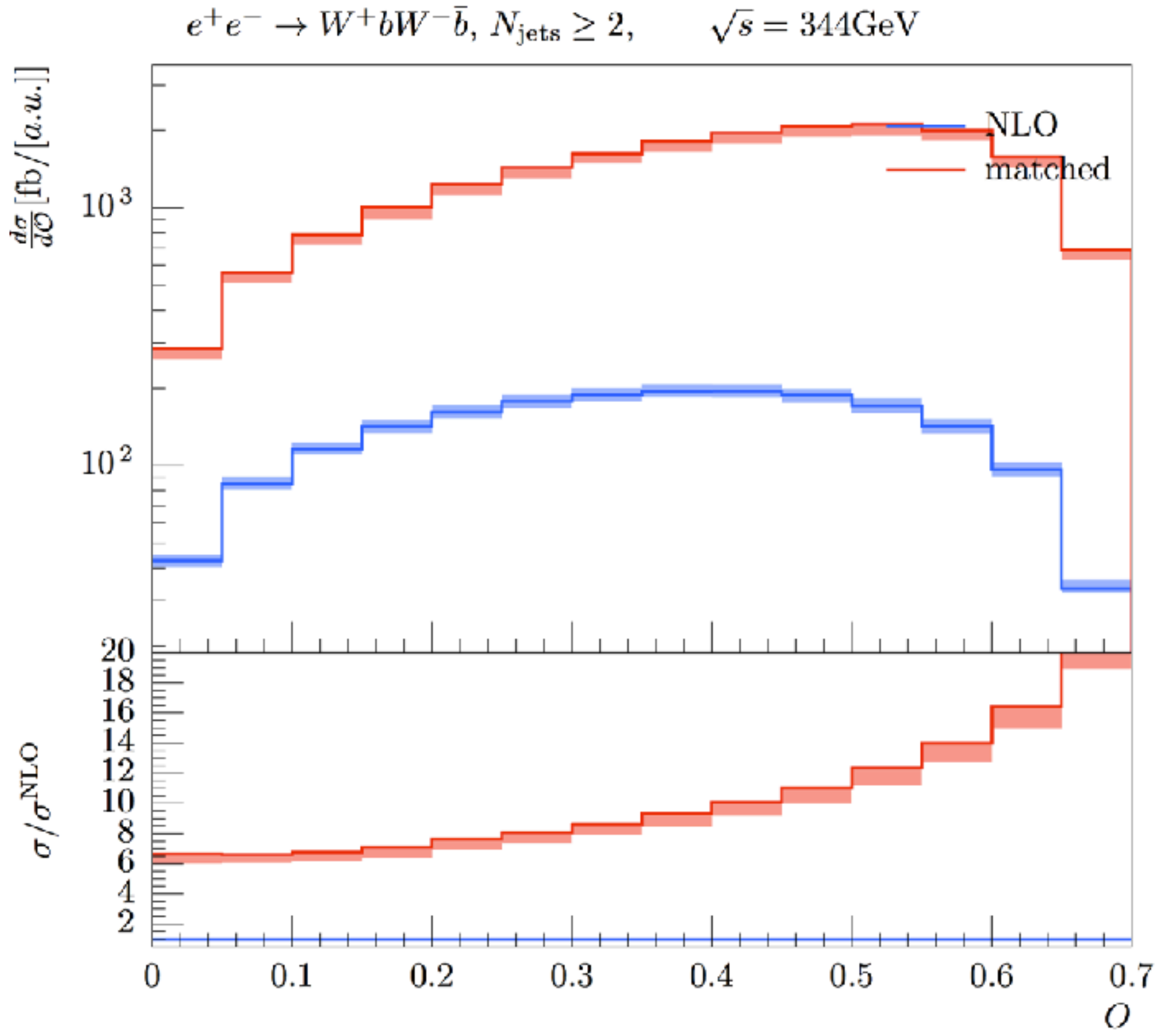
	n_ϵ	$n_\uparrow$	r_3	remarks
$\mathbf{3}\otimes\mathbf{3}\otimes\mathbf{6}\otimes\bar{\mathbf{6}}\otimes\bar{\mathbf{6}}$	0	4	4	
$\mathbf{3}\otimes\bar{\mathbf{3}}\otimes\mathbf{6}\otimes\bar{\mathbf{6}}\otimes\mathbf{8}$	0	4	5	but $r_2 = 4$
$\mathbf{6}\otimes\mathbf{6}\otimes\bar{\mathbf{6}}\otimes\bar{\mathbf{6}}\otimes\mathbf{8}$	0	5	8	but $r_2 = 6$
$\mathbf{3}\otimes\mathbf{3}\otimes\mathbf{3}\otimes\bar{\mathbf{3}}\otimes\bar{\mathbf{6}}$	1	0	3	
$\mathbf{3}\otimes\mathbf{3}\otimes\mathbf{3}\otimes\mathbf{3}\otimes\mathbf{6}$	2	0	2	
$\mathbf{3}\otimes\mathbf{6}\otimes\bar{\mathbf{6}}\otimes\bar{\mathbf{6}}\otimes\bar{\mathbf{6}}$	2	0	3	
$\mathbf{3}\otimes\bar{\mathbf{3}}\otimes\mathbf{6}\otimes\mathbf{6}\otimes\mathbf{6}$	2	1	3	
$\mathbf{6}\otimes\mathbf{6}\otimes\mathbf{6}\otimes\mathbf{8}\otimes\mathbf{8}$	2	2	10	4 anti-, 6 symmetric
$\mathbf{3}\otimes\mathbf{6}\otimes\mathbf{6}\otimes\mathbf{6}\otimes\mathbf{6}$	3	0	3	
$\mathbf{6}\otimes\bar{\mathbf{6}}\otimes\bar{\mathbf{6}}\otimes\bar{\mathbf{6}}\otimes\bar{\mathbf{6}}$	3	0	6	

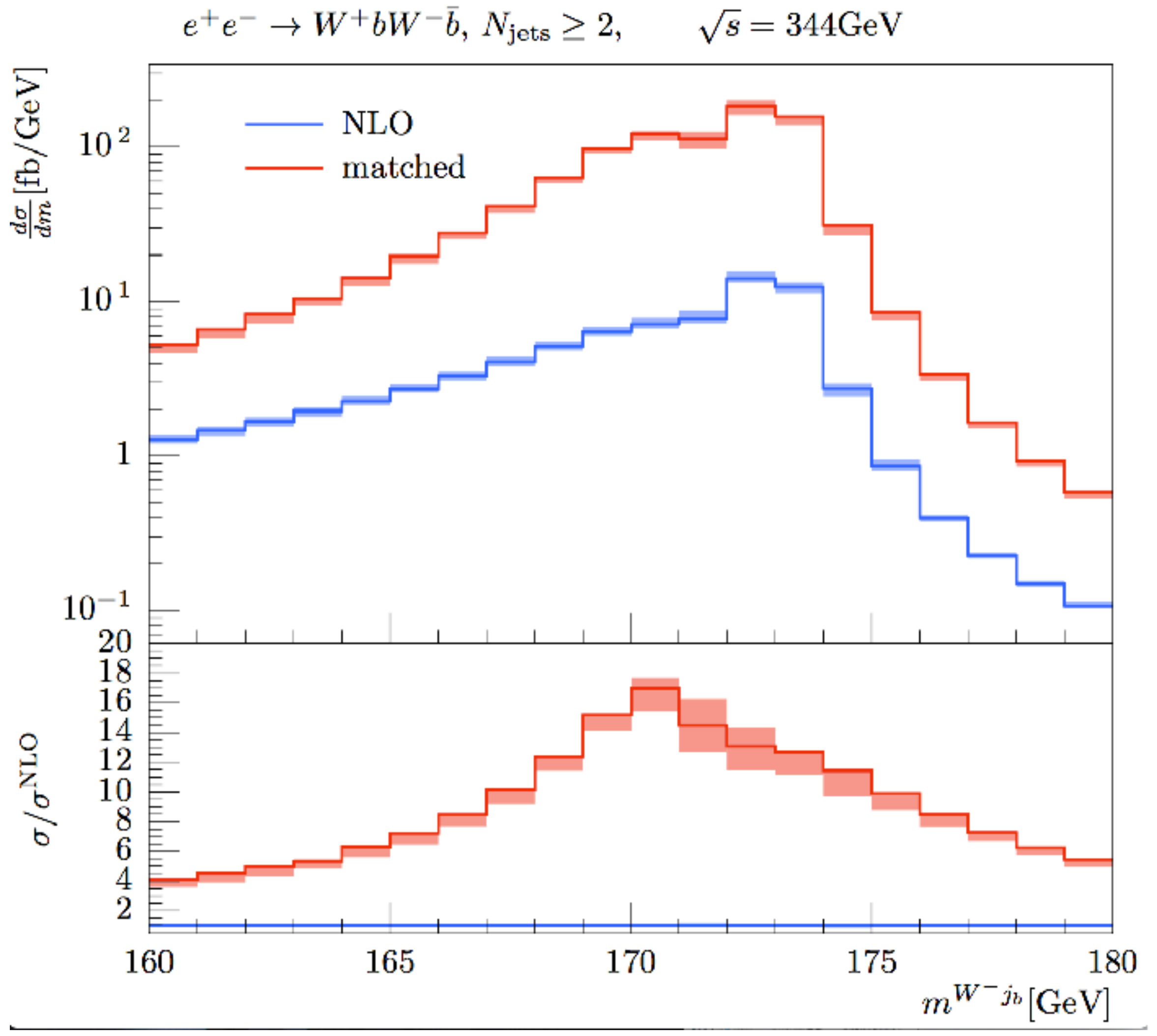
Quick note on the top threshold

Chokoufé/Hoang/Kilian/JRR/Stahlhofen/Teubner/Weiss, 1712.02220

- Exclusive Top threshold NLL-NLO QCD matched available
- Implemented for v2.5.1, revalidated in v3.0 parallelized
- Recent improvement in axial form factor matching
- New development line for upcoming versions
- Also work for top threshold handling in *pp* collisions!





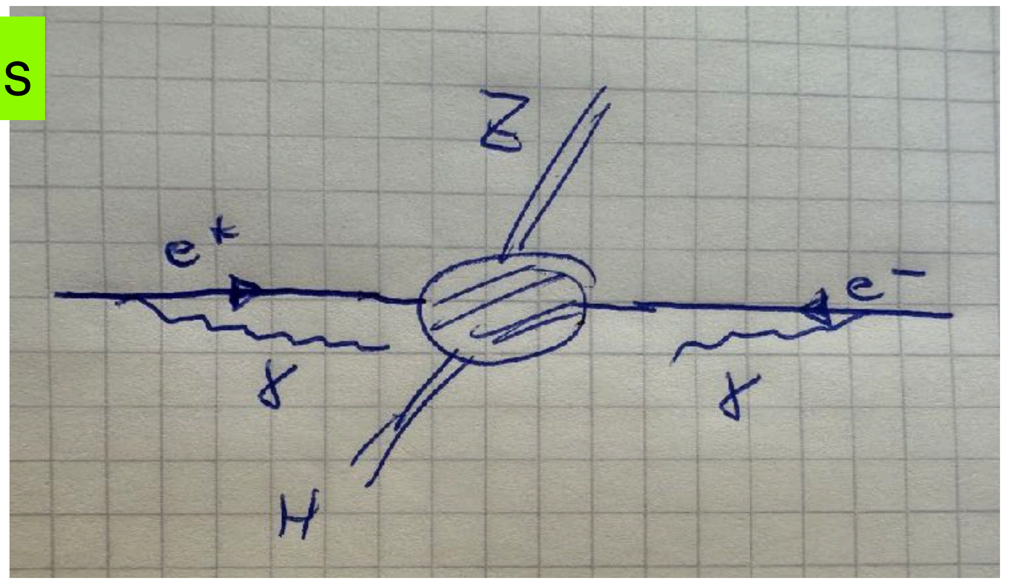



```
model = SM_tt_threshold

nrqcd_order = 1
FF = 1    ! NLL resummed
mpole_fixed = 1
Vtb = 1
m1S = 172 GeV
scale = m1S

$method = "threshold"
process eett_threshold = E1, e1 => Wp, Wm, b, B {
  $restrictions = "3+5~t && 4+6~tbar" nlo_calculation = real }

sqrts = 350 GeV
integrate (eett_threshold)
```

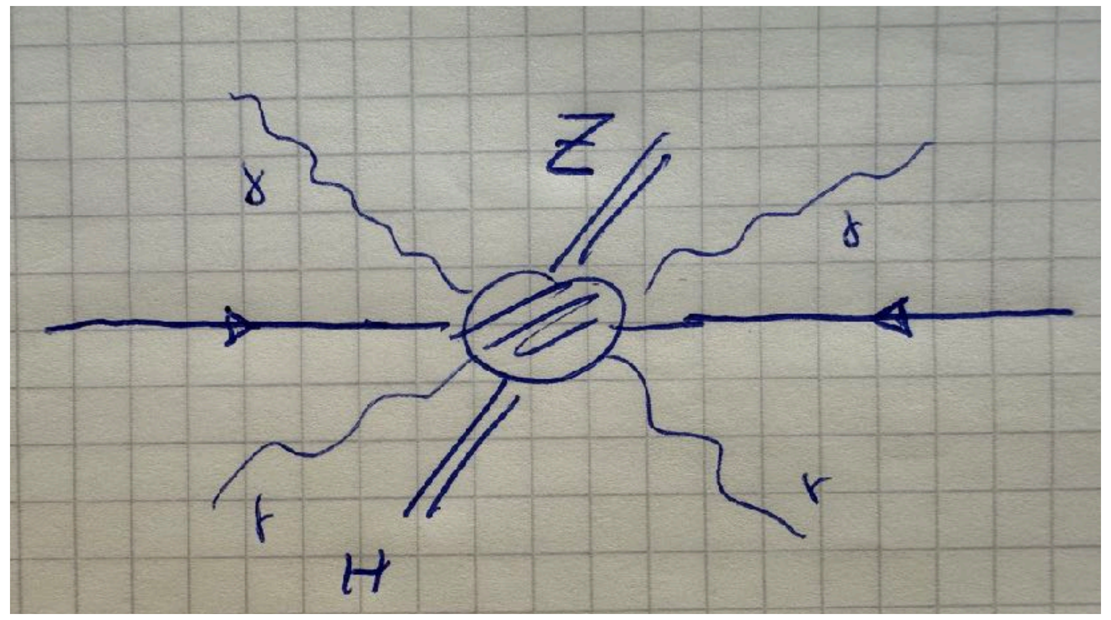
Further work on QED: ePDFs, EW PDFs, QED shower

Collinear logarithms

$$L = \log \frac{Q^2}{m^2}$$



$$\sigma = \alpha^b \sum_{n=0}^{\infty} \alpha^n \sum_{i=0}^{n} \sum_{j=0}^{n} \varsigma_{n,i,j} L^i \ell^j$$



Soft logarithms

$$\ell = \log \frac{Q^2}{\langle E_\gamma \rangle^2}$$

- Collinear resummation LO/LL   Gribov/Lipatov, 1972; Kuraev/Fadin, 1985; Skrzypek/Jadach, 1992; Cacciari/Deandrea/Montagna/Nicrosini, 199
- NLO QED PDFs, collinear evolution @ NLL   Frixione, 1909.0388; Bertone/Cacciari/Frixione/Stagnitto, 1911.12040 + 2207.03265
- Status in WHIZARD: LO+LL ePDFs fully functional, NLO+NLL ePDFs implemented (incl. NLO QED evol.), validated, functional for Born processes
- Crucial: numerical stability at kinematically peaked limit $z \to 1$
- Final infrastructure done, mapping for real radiation component (⇒ no plots yet ☹)

$$d\sigma_{kl}(p_k, p_l) = \sum_{ij=e^+,e^-,\gamma} \int dz_+ dz_- \Gamma_{i/k}(z_+, \mu^2, m^2) \Gamma_{j/l}(z_-, \mu^2, m^2) \times d\hat{\sigma}_{ij}(z_+ p_k, z_- p_l, \mu^2) + \mathcal{O}\left(\left(\frac{m^2}{s}\right)^p\right)$$

$$\mathbb{P}_S = \begin{pmatrix} P_{\Sigma\Sigma} & P_{\Sigma\gamma} \\ P_{\gamma\Sigma} & P_{\gamma\gamma} \end{pmatrix},$$

$$P_{NS} = P_{e^\pm e^\pm} - P_{e^\pm e^\mp} \equiv P^V_{ee} - P^V_{e\bar{e}}.$$

ePDFs for polarized leptons !?

P. Bredt/T. Striegl, 2024

Electron PDFs: some details

- Rewriting of analytic expressions in redundant variables $x, \bar{x} \equiv 1 - x$
- 1. step: numerically stable logs and polylogs
- 2. step: solve integrals for which only numerical solutions existed
- NLL ePDF is in form to allow for exponential mappings
- Quadruple precision only for critical points

$$
\begin{aligned}
\hat{J}^{\text{NLL}}_{\text{S,2,an}} = \frac{1}{108 b_0 z\left(z^2-1\right)} \times \Big(& 608 b_0 N_F^2 z^5 + 192 b_0 L_0 N_F^2 z^5 - 432 b_0 N_F z^5 + 96 b_0 N_F \pi^2 z^5 - 960 b_0^2 N_F \pi z^5 + \\
& 1152 b_1 N_F \pi z^5 + 1152 b_0^2 L_0 N_F \pi z^5 + 144 b_0 N_F^2 z^4 + 144 b_0 L_0 N_F^2 z^4 - 486 b_0 z^4 - 405 b_0 L_0 z^4 - 3852 b_0 N_F z^4 + \\
& 1656 b_0 L_0 N_F z^4 + 360 b_0^2 \pi^3 z^4 + 432 b_0^3 \pi^2 z^4 + 324 b_0 \pi^2 z^4 - 432 b_0 b_1 \pi^2 z^4 - 432 b_0^3 L_0 \pi^2 z^4 + 216 b_0 L_0 \pi^2 z^4 + \\
& 120 b_0 N_F \pi^2 z^4 + 432 b_1 \pi z^4 + 432 b_0^2 L_0 \pi z^4 - 3984 b_0^2 N_F \pi z^4 + 864 b_1 N_F \pi z^4 + 864 b_0^2 L_0 N_F \pi z^4 - 1328 b_0 N_F^2 z^3 - \\
& 336 b_0 L_0 N_F^2 z^3 + 1350 b_0 z^3 - 1539 b_0 L_0 z^3 + 4092 b_0 N_F z^3 - 1656 b_0 L_0 N_F z^3 - 360 b_0^2 \pi^3 z^3 - 432 b_0^3 \pi^2 z^3 - \\
& 504 b_0 \pi^2 z^3 + 432 b_0 b_1 \pi^2 z^3 + 432 b_0^3 L_0 \pi^2 z^3 - 216 b_0 L_0 \pi^2 z^3 - 216 b_0 N_F \pi^2 z^3 - 1080 b_0^2 \pi z^3 + 1296 b_1 \pi z^3 + \\
& 1296 b_0^2 L_0 \pi z^3 + 3504 b_0^2 N_F \pi z^3 - 2016 b_1 N_F \pi z^3 - 2016 b_0^2 L_0 N_F \pi z^3 - 176 b_0 N_F^2 z^2 - 336 b_0 L_0 N_F^2 z^2 + \\
& 486 b_0 z^2 + 405 b_0 L_0 z^2 + 5004 b_0 N_F z^2 - 1656 b_0 L_0 N_F z^2 - 648 b_0^2 \pi^3 z^2 - 432 b_0^3 \pi^2 z^2 + 108 b_0 \pi^2 z^2 + \\
& 432 b_0 b_1 \pi^2 z^2 + 432 b_0^3 L_0 \pi^2 z^2 - 216 b_0 L_0 \pi^2 z^2 - 216 b_0 N_F \pi^2 z^2 - 432 b_1 \pi z^2 - 432 b_0^2 L_0 \pi z^2 + 6672 b_0^2 N_F \pi z^2 - \\
& 2016 b_1 N_F \pi z^2 - 2016 b_0^2 L_0 N_F \pi z^2 + 720 b_0 N_F^2 z + 144 b_0 L_0 N_F^2 z - 1350 b_0 z + 1539 b_0 L_0 z - 3660 b_0 N_F z + \\
& 1656 b_0 L_0 N_F z + 864 b_0 (z-1) \Big((\log(z+1) - \log(1-z)) z^2 + \log(1-z) - \log(z+1) - 5 \log(2) \Big) \text{Li}_2\left(\frac{1-z}{2}\right) z - \\
& 4z \Big(\log(z) z^3 + \log(1-z) z - \log(1-z) + \log(z) + (z(z+6)-5) \log(z+1) \Big) \Big) \text{Li}_2(-z) + 8z \Big((z-1) \Big(- \\
& 4z^2 + 2z - 6 \log(1-z) + 6 b_0 \pi + 3 \Big) - 2 \left(z^3 + 5z - 4\right) \log(z+1) \Big) \text{Li}_2\left(\frac{1}{z+1}\right) + 4\left(z^2-1\right)(z(5z-8) + \\
& 10(z-1) z \log(z+1) - 6) \text{Li}_2\left(\frac{z}{z+1}\right) + 8z\left(z^2-1\right)(3z + 4 N_F (z+1) + 8) \text{Li}_3(1-z) - 8z(6 N_F + z) \Big(z^2 - \\
& 1 \Big) \text{Li}_3\left(\frac{z-1}{z}\right) + 8z(z+1)(z(7z-16)+7) \text{Li}_3(-z) + 4z(8z N_F + 20 N_F + 3z + 9)\left(z^2-1\right) \text{Li}_3(z) + 16z(z + \\
& 1)(z(3z-4)+3) \text{Li}_3\left(\frac{1}{z+1}\right) - z(16 N_F (z-1)(z+1)(2z+5) + z(z(21z+67)+99) - 107)\zeta(3) \Big) \Big) - \\
& 216 b_0 (z-1)(z+1)(z(9z+7)+3) \log^2(2) + 96 b_0 N_F \pi^2 - 2688 b_0^2 N_F \pi + 1152 b_1 N_F \pi + 1152 b_0^2 L_0 N_F \pi \Big)
\end{aligned}
$$

P. Bredt/T. Striegl, 2024

Electron PDFs: some details

- Rewriting of analytic expressions in redundant variables $x, \bar{x} \equiv 1 - x$
- 1. step: numerically stable logs and polylogs
- 2. step: solve integrals for which only numerical solutions existed
- NLL ePDF is in form to allow for exponential mappings
- Quadruple precision only for critical points

```
* Full NLL electron PDFs:
* Q = 1.0000E+00 GeV, NLL, alpha fixed:

  ePDF (x =    1.000000000000000E-44, S/NS/ELE/POS/GAM) =      1.131183E+42     1.290173E+06     5.655916E+41     5.655916E+41     5.078808E+43
  ePDF (x =    1.000000000000000E-44, e- - [S + NS]/2) = 0.00000000
  ePDF (x =    1.000000000000000E-44, e+ - [S - NS]/2) = 0.00000000
  ePDF (x =    1.000000000000000E-43, S/NS/ELE/POS/GAM) =      1.106221E+41     7.885546E+04     5.531106E+40     5.531106E+40     4.968602E+42
  ePDF (x =    1.000000000000000E-43, e- - [S + NS]/2) = 0.00000000
  ePDF (x =    1.000000000000000E-43, e+ - [S - NS]/2) = 0.00000000
  ePDF (x =    1.000000000000000E-42, S/NS/ELE/POS/GAM) =      1.081259E+40    -8.861889E+03     5.406296E+39     5.406296E+39     4.858498E+41
  ePDF (x =    1.000000000000000E-42, e- - [S + NS]/2) = 0.00000000
  ePDF (x =    1.000000000000000E-42, e+ - [S - NS]/2) = 0.00000000
  ePDF (x =    1.000000000000000E-41, S/NS/ELE/POS/GAM) =      1.056297E+39     1.200275E+03     5.281486E+38     5.281486E+38     4.748496E+40
  ePDF (x =    1.000000000000000E-41, e- - [S + NS]/2) = 0.00000000
  ePDF (x =    1.000000000000000E-41, e+ - [S - NS]/2) = 0.00000000
  ePDF (x =    1.000000000000000E-40, S/NS/ELE/POS/GAM) =      1.031335E+38     2.082260E+02     5.156676E+37     5.156676E+37     4.638596E+39
  ePDF (x =    1.000000000000000E-40, e- - [S + NS]/2) = 0.00000000
  ePDF (x =    1.000000000000000E-40, e+ - [S - NS]/2) = 0.00000000
  ePDF (x =    1.000000000000000E-39, S/NS/ELE/POS/GAM) =      1.006373E+37     1.717684E+01     5.031866E+36     5.031866E+36     4.528797E+38
  ePDF (x =    1.000000000000000E-39, e- - [S + NS]/2) = 0.00000000
  ePDF (x =    1.000000000000000E-39, e+ - [S - NS]/2) = 0.00000000
  ePDF (x =    1.000000000000000E-38, S/NS/ELE/POS/GAM) =      9.814112E+35     7.520304E-01     4.907056E+35     4.907056E+35     4.419100E+37
  ePDF (x =    1.000000000000000E-38, e- - [S + NS]/2) = 0.00000000
  ePDF (x =    1.000000000000000E-38, e+ - [S - NS]/2) = 0.00000000
  ePDF (x =    1.000000000000000E-37, S/NS/ELE/POS/GAM) =      9.564492E+34    -4.189107E-01     4.782246E+34     4.782246E+34     4.309505E+36
  ePDF (x =    1.000000000000000E-37, e- - [S + NS]/2) = 0.00000000
  ePDF (x =    1.000000000000000E-37, e+ - [S - NS]/2) = 0.00000000
  ePDF (x =    1.000000000000000E-36, S/NS/ELE/POS/GAM) =      9.314872E+33    -2.591904E-01     4.657436E+33     4.657436E+33     4.200012E+35
  ePDF (x =    1.000000000000000E-36, e- - [S + NS]/2) = 0.50000000
  ePDF (x =    1.000000000000000E-36, e+ - [S - NS]/2) = 0.50000000
  ePDF (x =    1.000000000000000E-35, S/NS/ELE/POS/GAM) =      9.065252E+32    -2.549587E-01     4.532626E+32     4.532626E+32     4.090620E+34
  ePDF (x =    1.000000000000000E-35, e- - [S + NS]/2) = 0.00000000
  ePDF (x =    1.000000000000000E-35, e+ - [S - NS]/2) = 0.00000000
  ePDF (x =    1.000000000000000E-34, S/NS/ELE/POS/GAM) =      8.815632E+31    -2.321432E-01     4.407816E+31     4.407816E+31     3.981331E+33
  ePDF (x =    1.000000000000000E-34, e- - [S + NS]/2) = 0.01562500
  ePDF (x =    1.000000000000000E-34, e+ - [S - NS]/2) = 0.00000000
  ePDF (x =    1.000000000000000E-33, S/NS/ELE/POS/GAM) =      8.566012E+30    -2.133651E-01     4.283006E+30     4.283006E+30     3.872143E+32
```

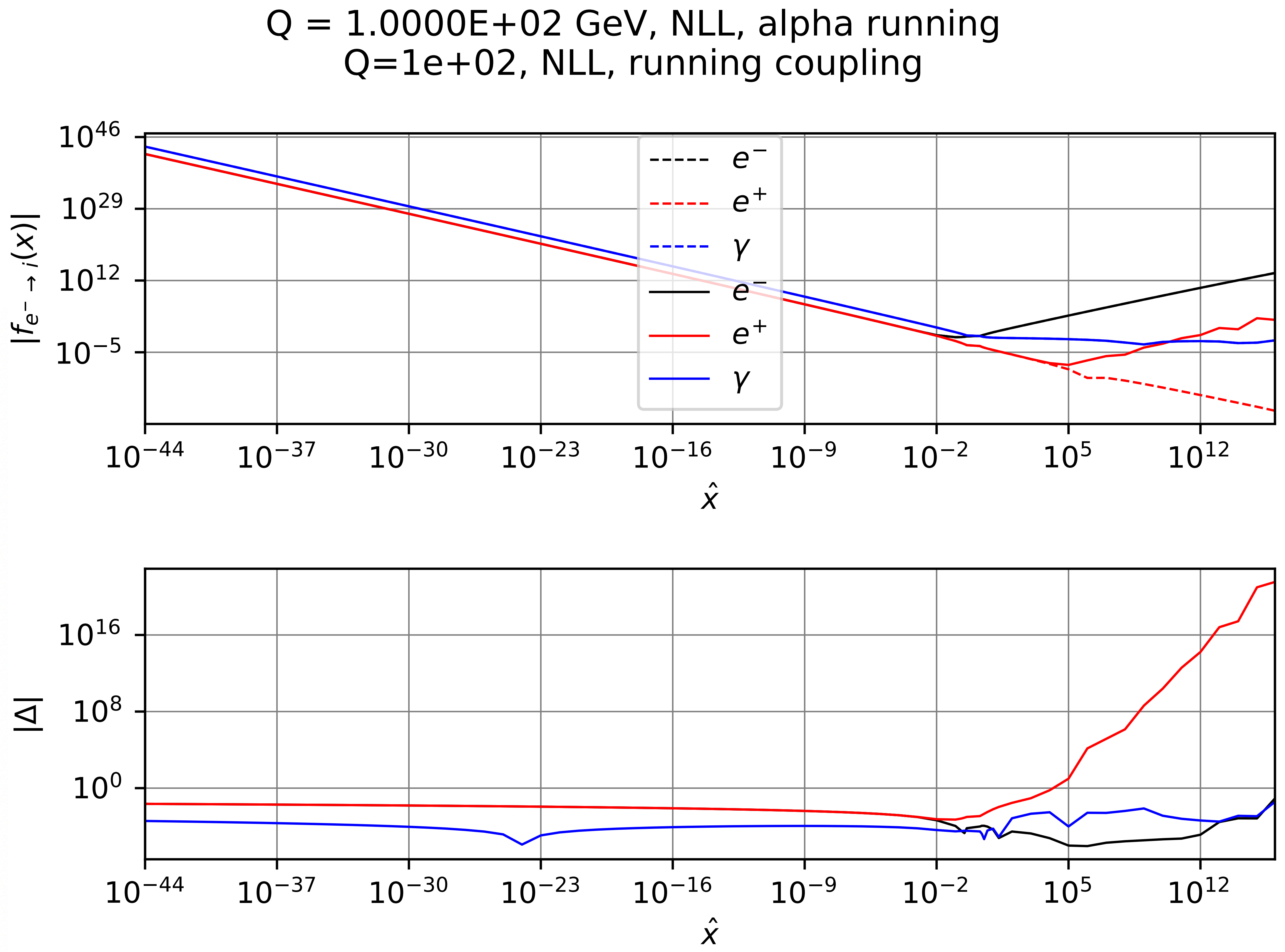
$$
\begin{aligned}
\hat{J}^{\rm NLL}_{\rm S,2,an} = {} & \frac{1}{108 b_0 z\left(z^2-1\right)} \times \Big(608 b_0 N_F^2 z^5 + 192 b_0 L_0 N_F^2 z^5 - 432 b_0 N_F z^5 + 96 b_0 N_F \pi^2 z^5 - 960 b_0^2 N_F \pi z^5 + \\
& 1152 b_1 N_F \pi z^5 + 1152 b_0^2 L_0 N_F \pi z^5 + 144 b_0 N_F^2 z^4 + 144 b_0 L_0 N_F^2 z^4 - 486 b_0 z^4 - 405 b_0 L_0 z^4 - 3852 b_0 N_F z^4 + \\
& 1656 b_0 L_0 N_F z^4 + 360 b_0^2 \pi^3 z^4 + 432 b_0^3 \pi^2 z^4 + 324 b_0 \pi^2 z^4 - 432 b_0 b_1 \pi^2 z^4 - 432 b_0^3 L_0 \pi^2 z^4 + 216 b_0 L_0 \pi^2 z^4 + \\
& 120 b_0 N_F \pi^2 z^4 + 432 b_1 \pi z^4 + 432 b_0^2 L_0 \pi z^4 - 3984 b_0^2 N_F \pi z^4 + 864 b_1 N_F \pi z^4 + 864 b_0^2 L_0 N_F \pi z^4 - 1328 b_0 N_F^2 z^3 - \\
& 336 b_0 L_0 N_F^2 z^3 + 1350 b_0 z^3 - 1539 b_0 L_0 z^3 + 4092 b_0 N_F z^3 - 1656 b_0 L_0 N_F z^3 - 360 b_0^2 \pi^3 z^3 - 432 b_0^3 \pi^2 z^3 - \\
& 504 b_0 \pi^2 z^3 + 432 b_0 b_1 \pi^2 z^3 + 432 b_0^3 L_0 \pi^2 z^3 - 216 b_0 L_0 \pi^2 z^3 - 216 b_0 N_F \pi^2 z^3 - 1080 b_0^2 \pi z^3 + 1296 b_1 \pi z^3 + \\
& 1296 b_0^2 L_0 \pi z^3 + 3504 b_0^2 N_F \pi z^3 - 2016 b_1 N_F \pi z^3 - 2016 b_0^2 L_0 N_F \pi z^3 - 176 b_0 N_F^2 z^2 - 336 b_0 L_0 N_F^2 z^2 + \\
& 486 b_0 z^2 + 405 b_0 L_0 z^2 + 5004 b_0 N_F z^2 - 1656 b_0 L_0 N_F z^2 - 648 b_0^2 \pi^3 z^2 - 432 b_0^3 \pi^2 z^2 + 108 b_0 \pi^2 z^2 + \\
& 432 b_0 b_1 \pi^2 z^2 + 432 b_0^3 L_0 \pi^2 z^2 - 216 b_0 L_0 \pi^2 z^2 - 216 b_0 N_F \pi^2 z^2 - 432 b_1 \pi z^2 - 432 b_0^2 L_0 \pi z^2 + 6672 b_0^2 N_F \pi z^2 - \\
& 2016 b_1 N_F \pi z^2 - 2016 b_0^2 L_0 N_F \pi z^2 + 720 b_0 N_F^2 z + 144 b_0 L_0 N_F^2 z - 1350 b_0 z + 1539 b_0 L_0 z - 3660 b_0 N_F z + \\
& 1656 b_0 L_0 N_F z + 864 b_0 (z-1)\Big((\log(z+1) - \log(1-z)) z^2 + \log(1-z) - \log(z+1) - 5\log(2)\Big) \mathrm{Li}_2\left(\frac{1-z}{2}\right) z - \\
& 4z\Big(\log(z) z^3 + \log(1-z) z - \log(1-z) + \log(z) + (z(z+6)-5)\log(z+1)\Big)\Big) \mathrm{Li}_2(-z) + 8z\Big((z-1)\Big(- \\
& 4z^2 + 2z - 6\log(1-z) + 6 b_0 \pi + 3\Big) - 2\left(z^3 + 5z - 4\right)\log(z+1)\Big)\mathrm{Li}_2\left(\frac{1}{z+1}\right) + 4\left(z^2-1\right)(z(5z-8) + \\
& 10(z-1)z\log(z+1) - 6)\mathrm{Li}_2\left(\frac{z}{z+1}\right) + 8z\left(z^2-1\right)(3z + 4N_F(z+1) + 8)\mathrm{Li}_3(1-z) - 8z(6N_F + z)\Big(z^2 - \\
& 1\Big)\mathrm{Li}_3\left(\frac{z-1}{z}\right) + 8z(z+1)(z(7z-16)+7)\mathrm{Li}_3(-z) + 4z(8zN_F + 20N_F + 3z + 9)\left(z^2-1\right)\mathrm{Li}_3(z) + 16z(z + \\
& 1)(z(3z-4)+3)\mathrm{Li}_3\left(\frac{1}{z+1}\right) - z(16N_F(z-1)(z+1)(2z+5) + z(z(21z+67)+99) - 107)\zeta(3)\Big)\Big) - \\
& 216 b_0 (z-1)(z+1)(z(9z+7)+3)\log^2(2) + 96 b_0 N_F \pi^2 - 2688 b_0^2 N_F \pi + 1152 b_1 N_F \pi + 1152 b_0^2 L_0 N_F \pi \Big)
\end{aligned}
$$

P. Bredt/T. Striegl, 2024

Electron PDFs: some details

- Rewriting of analytic expressions in redundant variables $x, \bar{x} \equiv 1 - x$
- 1. step: numerically stable logs and polylogs
- 2. step: solve integrals for which only numerical solutions existed
- NLL ePDF is in form to allow for exponential mappings
- Quadruple precision only for critical points

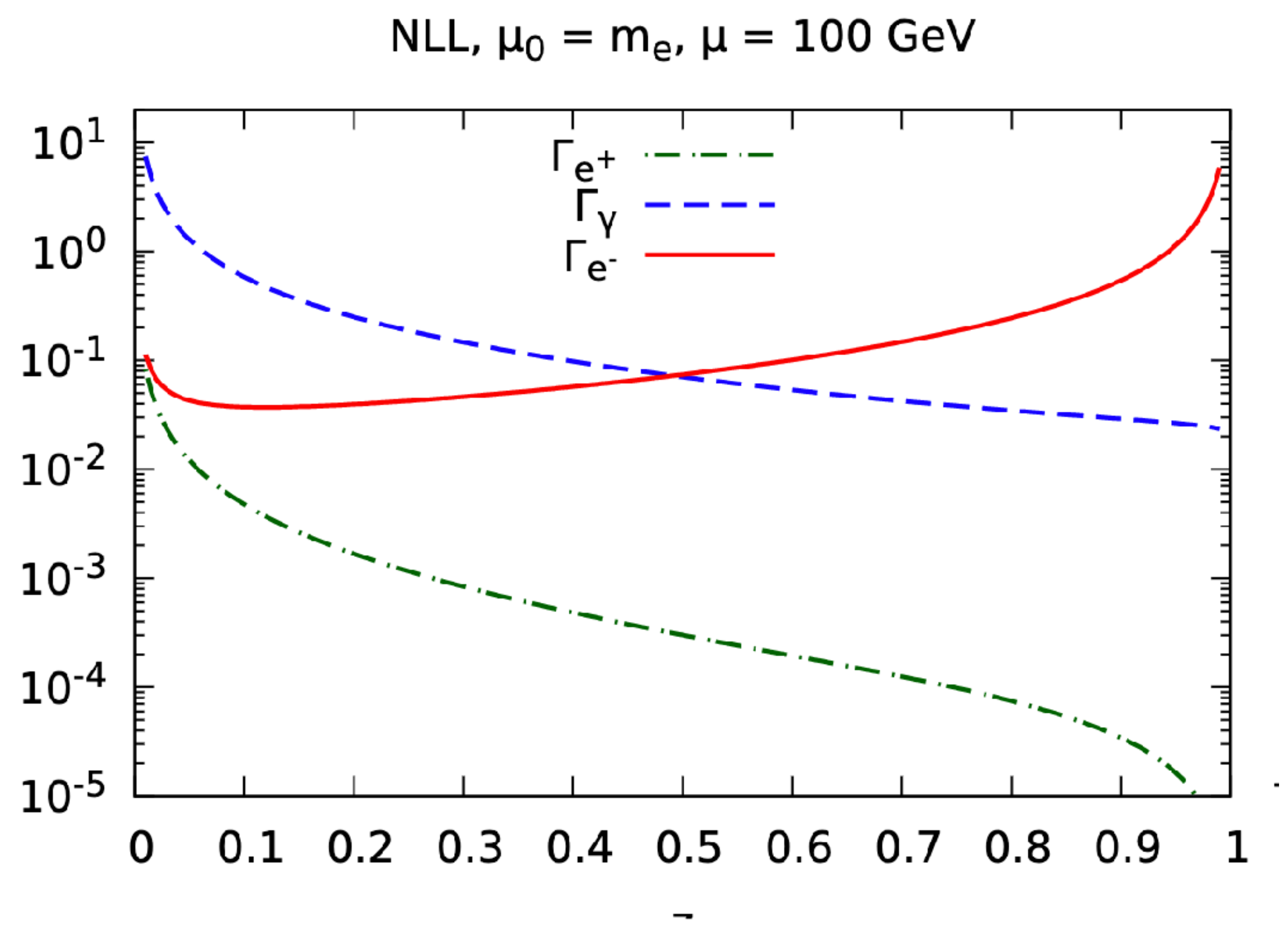
```
* Full NLL electron PDFs:
* Q = 1.0000E+00 GeV, NLL, alpha fixed:

  ePDF (x =    1.000000000000000E-44, S/NS/ELE/POS/GAM) =      1.131183E+42     1.290173E+06     5.655916E+41     5.655916E+41     5.078808E+43
  ePDF (x =    1.000000000000000E-44, e- - [S + NS]/2) = 0.00000000
  ePDF (x =    1.000000000000000E-44, e+ - [S - NS]/2) = 0.00000000
  ePDF (x =    1.000000000000000E-43, S/NS/ELE/POS/GAM) =      1.106221E+41     7.885546E+04     5.531106E+40     5.531106E+40     4.968602E+42
  ePDF (x =    1.000000000000000E-43, e- - [S + NS]/2) = 0.00000000
  ePDF (x =    1.000000000000000E-43, e+ - [S - NS]/2) = 0.00000000
  ePDF (x =    1.000000000000000E-42, S/NS/ELE/POS/GAM) =      1.081259E+40    -8.861889E+03     5.406296E+39     5.406296E+39     4.858498E+41
  ePDF (x =    1.000000000000000E-42, e- - [S + NS]/2) = 0.00000000
  ePDF (x =    1.000000000000000E-42, e+ - [S - NS]/2) = 0.00000000
  ePDF (x =    1.000000000000000E-41, S/NS/ELE/POS/GAM) =      1.056297E+39     1.200275E+03     5.281486E+38     5.281486E+38     4.748496E+40
  ePDF (x =    1.000000000000000E-41, e- - [S + NS]/2) = 0.00000000
  ePDF (x =    1.000000000000000E-41, e+ - [S - NS]/2) = 0.00000000
  ePDF (x =    1.000000000000000E-40, S/NS/ELE/POS/GAM) =      1.031335E+38     2.082260E+02     5.156676E+37     5.156676E+37     4.638596E+39
  ePDF (x =    1.000000000000000E-40, e- - [S + NS]/2) = 0.00000000
  ePDF (x =    1.000000000000000E-40, e+ - [S - NS]/2) = 0.00000000
  ePDF (x =    1.000000000000000E-39, S/NS/ELE/POS/GAM) =      1.006373E+37     1.717684E+01     5.031866E+36     5.031866E+36     4.528797E+38
  ePDF (x =    1.000000000000000E-39, e- - [S + NS]/2) = 0.00000000
  ePDF (x =    1.000000000000000E-39, e+ - [S - NS]/2) = 0.00000000
  ePDF (x =    1.000000000000000E-38, S/NS/ELE/POS/GAM) =      9.814112E+35     7.520304E-01     4.907056E+35     4.907056E+35     4.419100E+37
  ePDF (x =    1.000000000000000E-38, e- - [S + NS]/2) = 0.00000000
  ePDF (x =    1.000000000000000E-38, e+ - [S - NS]/2) = 0.00000000
  ePDF (x =    1.000000000000000E-37, S/NS/ELE/POS/GAM) =      9.564492E+34    -4.189107E-01     4.782246E+34     4.782246E+34     4.309505E+36
  ePDF (x =    1.000000000000000E-37, e- - [S + NS]/2) = 0.00000000
  ePDF (x =    1.000000000000000E-37, e+ - [S - NS]/2) = 0.00000000
  ePDF (x =    1.000000000000000E-36, S/NS/ELE/POS/GAM) =      9.314872E+33    -2.591904E-01     4.657436E+33     4.657436E+33     4.200012E+35
  ePDF (x =    1.000000000000000E-36, e- - [S + NS]/2) = 0.50000000
  ePDF (x =    1.000000000000000E-36, e+ - [S - NS]/2) = 0.50000000
  ePDF (x =    1.000000000000000E-35, S/NS/ELE/POS/GAM) =      9.065252E+32    -2.549587E-01     4.532626E+32     4.532626E+32     4.090620E+34
  ePDF (x =    1.000000000000000E-35, e- - [S + NS]/2) = 0.00000000
  ePDF (x =    1.000000000000000E-35, e+ - [S - NS]/2) = 0.00000000
  ePDF (x =    1.000000000000000E-34, S/NS/ELE/POS/GAM) =      8.815632E+31    -2.321432E-01     4.407816E+31     4.407816E+31     3.981331E+33
  ePDF (x =    1.000000000000000E-34, e- - [S + NS]/2) = 0.01562500
  ePDF (x =    1.000000000000000E-34, e+ - [S - NS]/2) = 0.00000000
  ePDF (x =    1.000000000000000E-33, S/NS/ELE/POS/GAM) =      8.566012E+30    -2.133651E-01     4.283006E+30     4.283006E+30     3.872143E+32
```



$\hat{x} = x$ for $x < 0.5$, $\hat{x} = 1/(1-x)$ for $x > 0.5$

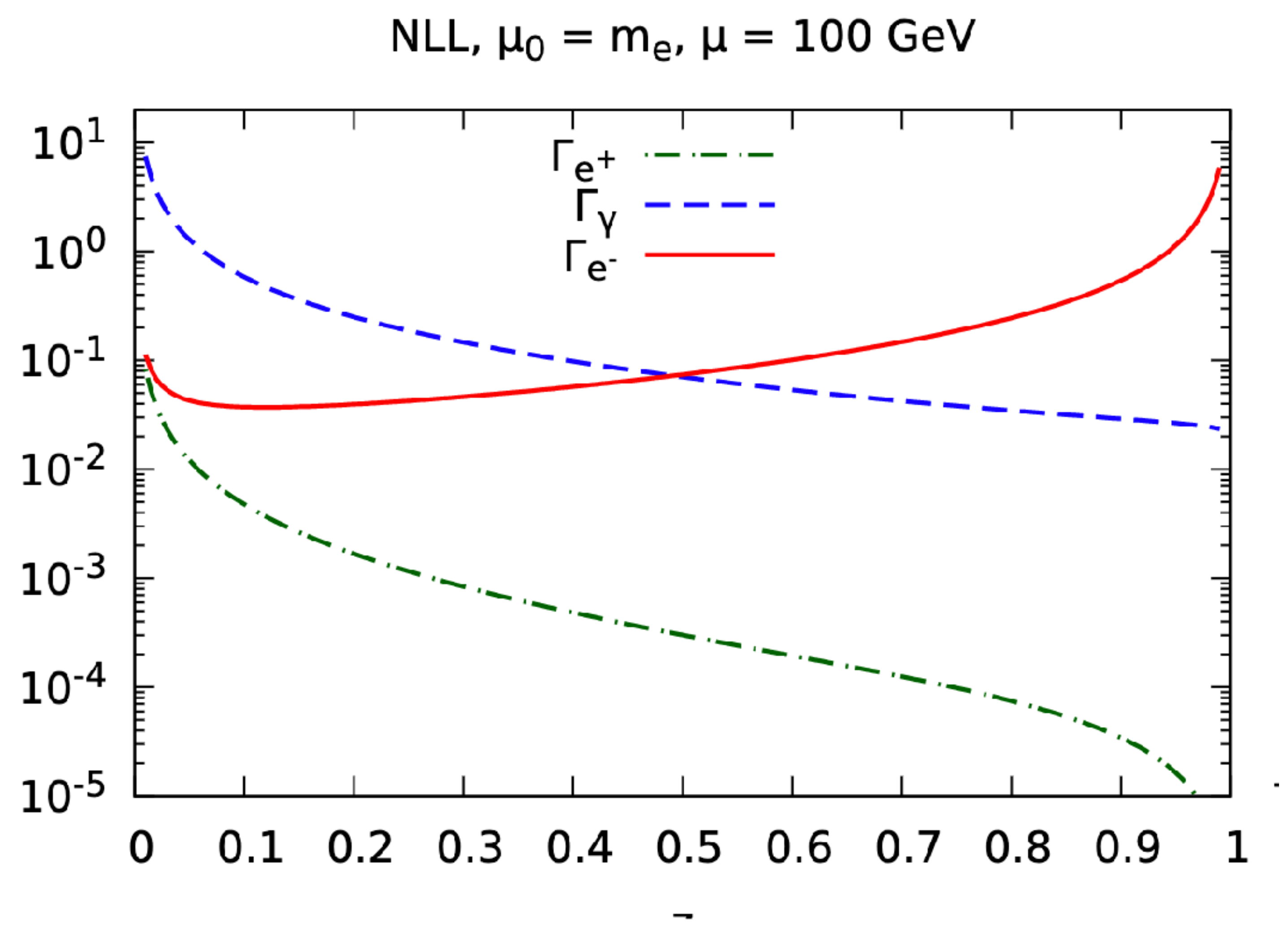
WHIZARD for $\mu^+\mu^-$ colliders and multi-TeV e^+e^- colliders

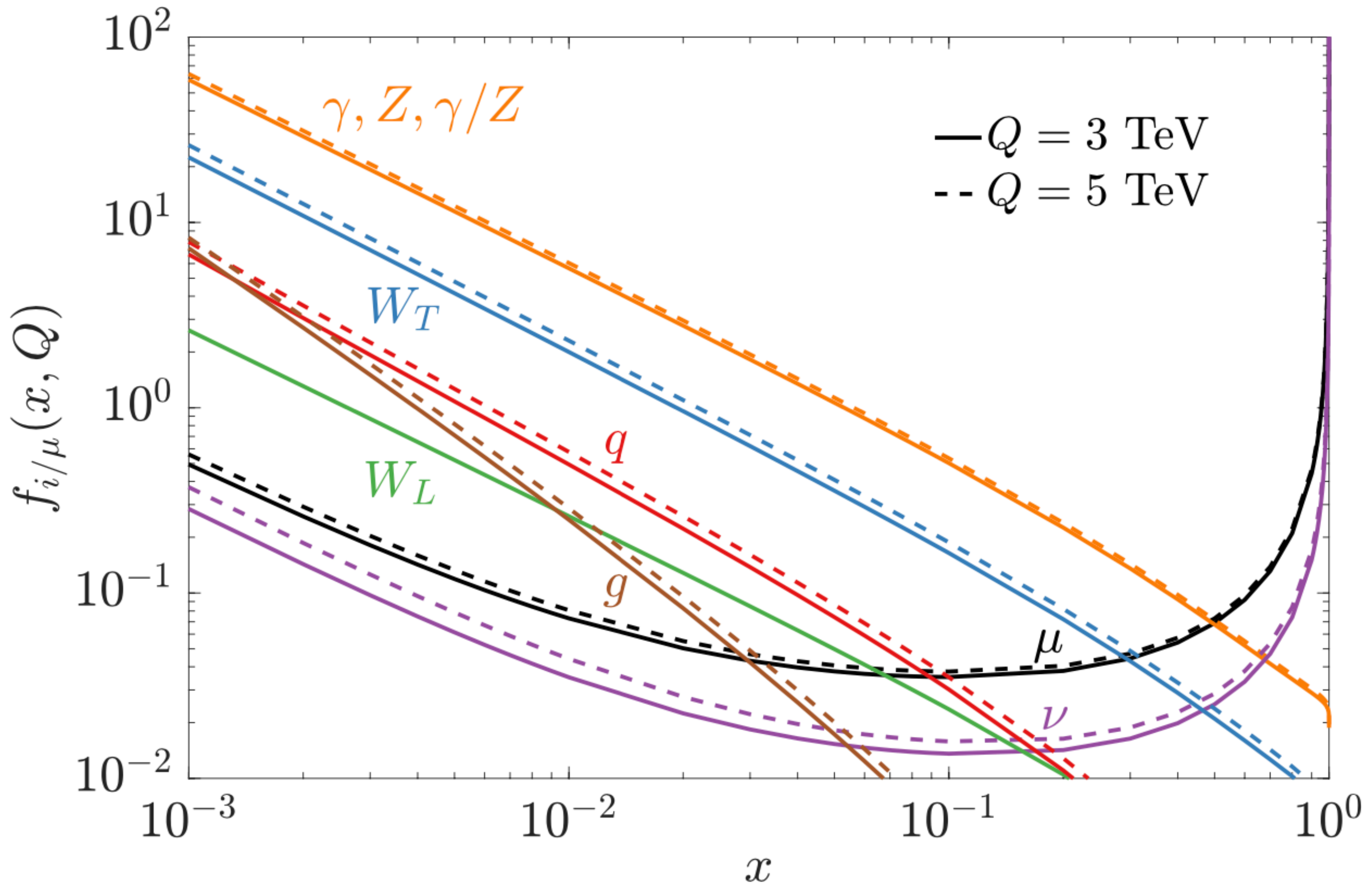
- Collinear factorization not in QED, but in full SM
  Han/Ma/Xie, 2007.14300, 2103.09844
- Ancient name (from SSC times!): EWA ("Effective *W* approximation)
- Fully inclusive in collinear/forward/beam direction
- Fast interpolation (CTEQ-like/LHAPDF-like) grids available
- Infrastructure completed in `Whizard` [Mękała/JRR]
- Validation against existing EWA implementation [Dahlén]



WHIZARD for $\mu^+\mu^-$ colliders and multi-TeV e^+e^- colliders

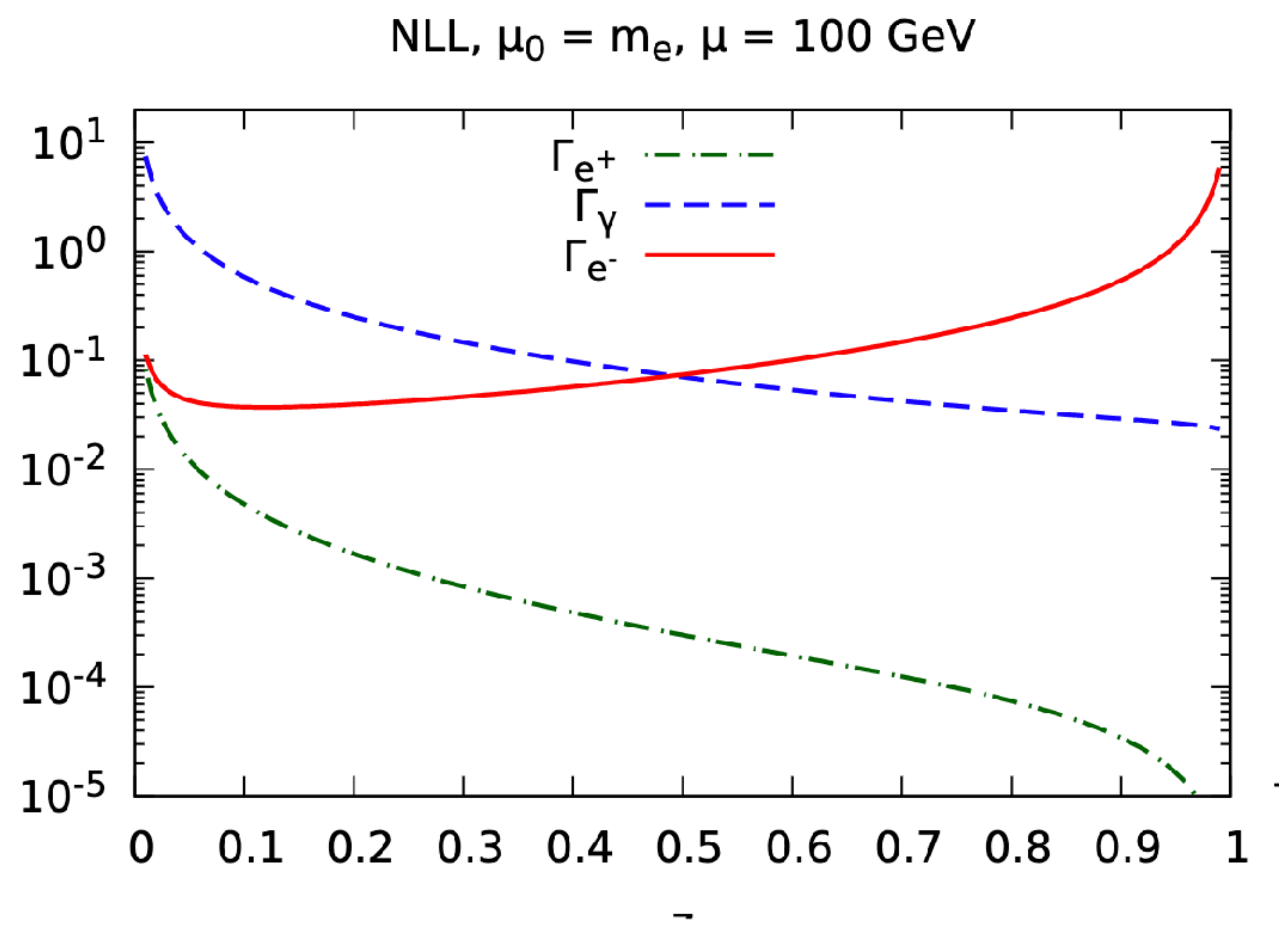
- Collinear factorization not in QED, but in full SM
  Han/Ma/Xie, 2007.14300, 2103.09844
- Ancient name (from SSC times!): EWA ("Effective *W* approximation)
- Fully inclusive in collinear/forward/beam direction
- Fast interpolation (CTEQ-like/LHAPDF-like) grids available
- Infrastructure completed in Whizard [Mękała/JRR]
- Validation against existing EWA implementation [Dahlén]



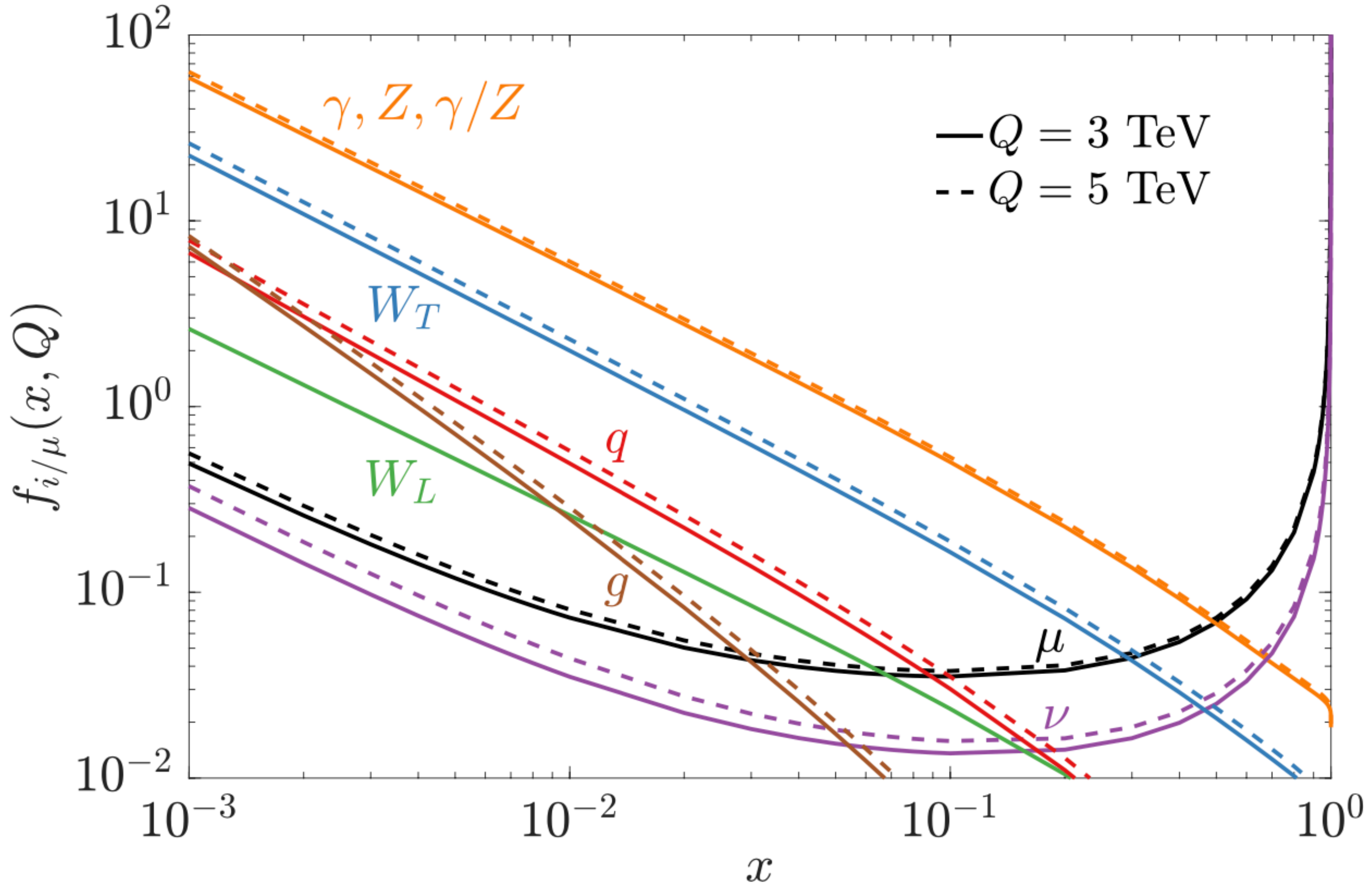


WHIZARD for $\mu^+\mu^-$ colliders and multi-TeV e^+e^- colliders

- Collinear factorization not in QED, but in full SM
  Han/Ma/Xie, 2007.14300, 2103.09844
- Ancient name (from SSC times!): EWA ("Effective *W* approximation)
- Fully inclusive in collinear/forward/beam direction
- Fast interpolation (CTEQ-like/LHAPDF-like) grids available
- Infrastructure completed in `Whizard` [Mękała/JRR]
- Validation against existing EWA implementation [Dahlén]



- $\gamma\gamma$ part (quasi-) identical to collinear QED lepton PDFs
- Necessitates a special incarnation of SM implementation for MEs
- Lots of tricky and dirty details in implementation



- Has to be accompanied by EW fragmentation functions (event selection!)

Simulation framework / bug fixes / new features

News on technicalities, work in progress, started projects:

- Interface to PYTHIA8: many bug fixes, but still lot of work to do (e.g. soft photon numerics)
- Bug fix (in v3.1.3) for beam simulations generating artefacts due to depleted regions (triggered by C^3)
- Bug fixes UFO interfaces: correct parsing of tokens, case-sensitiveness, allow backslash-escaped lines
- Issue resolved for *Z* pole running: numerical failure + technical bug fixed (led to artificial shift/jump in cross section)
- Simulation of LLP (long-lived particles) / displaced vertices, also with oscillations of particles (just started)
- Technically allow for muon collider beam spectra (not yet produced for WHIZARD/CIRCE2)
- EDM4HEP interface: implementation started, expected maybe already for ECFA workshop
- Soft/eikonal photon (YFS) resummation started: first results expected 2025
- Again: some refactoring started on internal data structures (triggered by in-house coupling ordered MEs)

Conclusions & Outlook

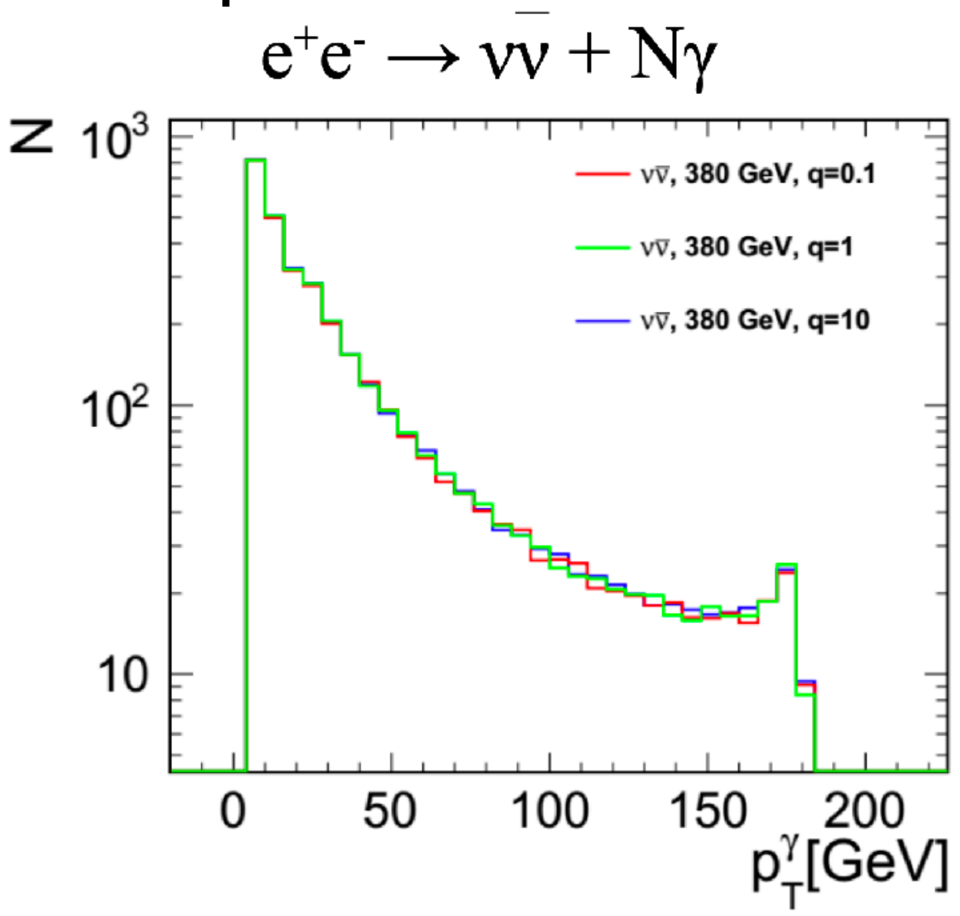
- Take-home message: `WHIZARD` is a full-fledged NLO Monte Carlo generator
- Highlights: NLO EW / NLO QCD for lepton colliders, NLO EW/QCD mixed corrections at LHC
- Loop-induced processes; NLO QCD for BSM models
- Generic POWHEG-type matching for NLO QCD ready, for NLO QED/EW starting
- Final preparations for in-house generation of exclusive coupling orders, fully general color structures
- Under development: EDM4HEP interface, NLL ePDFs, EWPDFs, displaced vertices / LLP, YFS, QED shower
- Caveat: many *“w.i.p”* or *“construction sites”* : limited person-power, looks more promising 2025

BACKUP

QED showers + matching: EW PDFs + EW shower

QED ISR [+FSR], matching

- "Shower-recoil approach": generate $p_\perp$ according to $\frac{\alpha}{\pi} \cdot \log \frac{p_\perp^2}{m_e^2}$
- Boost according to the generated $p_\perp$ (avail. for for ISR, EPA or ISR+EPA)
- Algorithm applied recursively (similar to massive NLO EWISR PS construction)
- Recursive algorithm resembles a photon shower with *n* exclusive photons
- Implementation is starting W. Kilian/JRR/T. Striegl



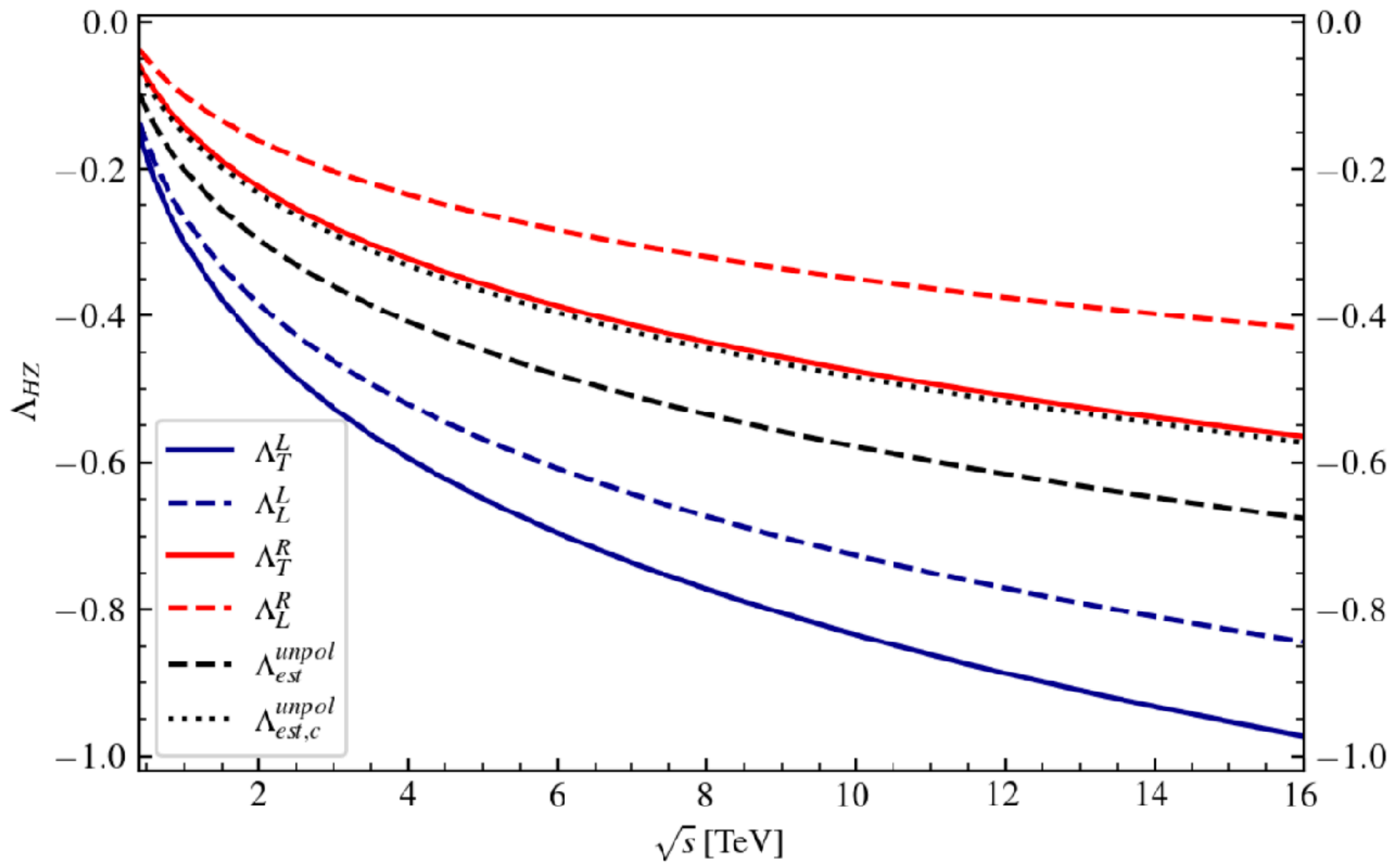
Kalinowski/Kotlarski/Mękała/Sopicki/Żarnecki, 2020

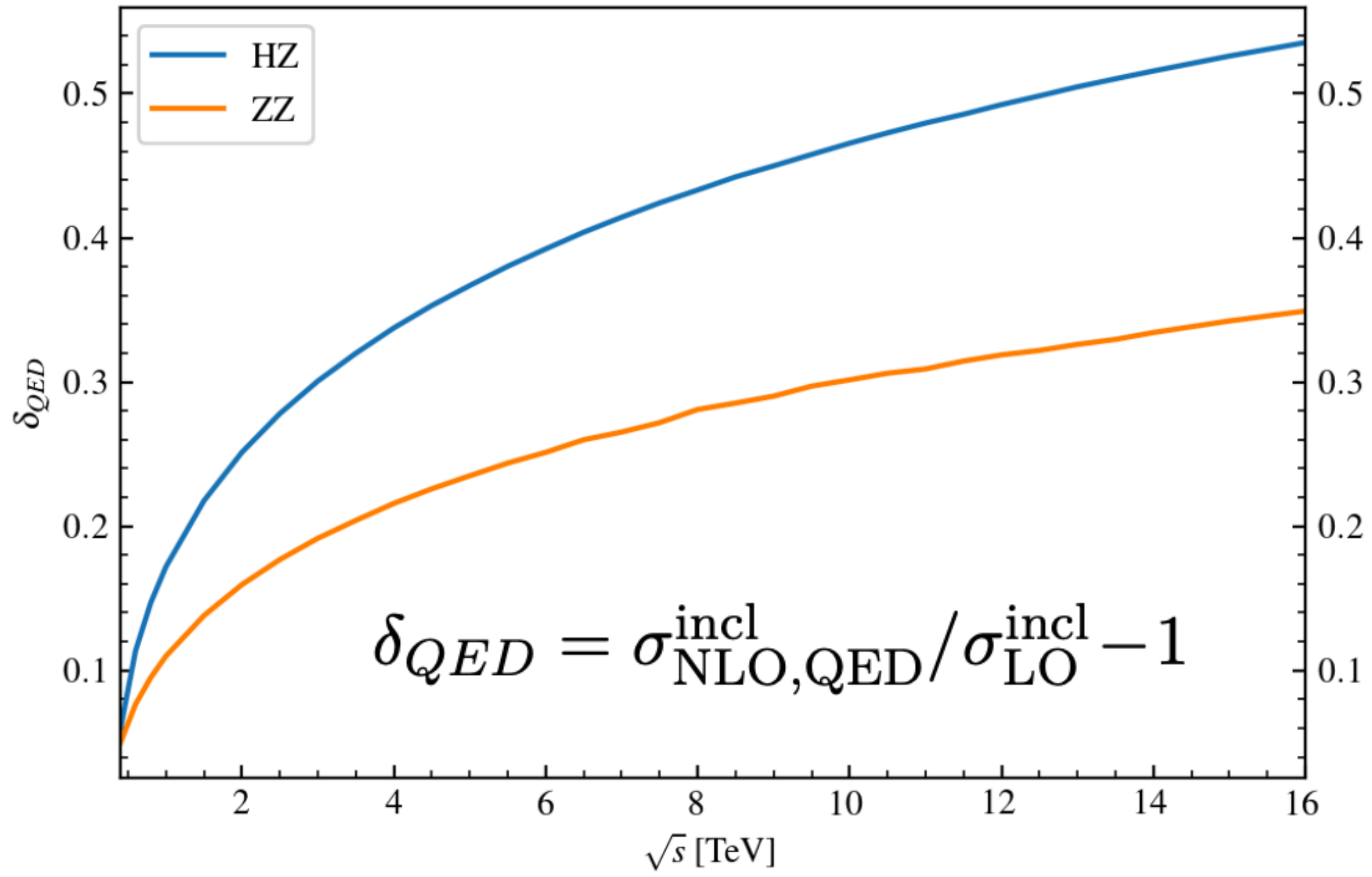
Full QED shower

- Based either on dipoles or antennae
- Can then be combined with POWHEG-type matching
- Implementation is starting [building on code infrastructure of `WHIZARD` QCD (virt.) shower]

Validation of the Sudakov regime

$\mu^+\mu^- \to X, \sqrt{s} = 10$ TeV	$\sigma^{\rm incl}_{\rm LO}$ [fb]	$\sigma^{\rm incl}_{\rm NLO}$ [fb]	$\delta_{\rm EW}$ [%]
W^+W^-	$5.8820(2) \cdot 10^{1}$	$6.11(1) \cdot 10^{1}$	$+3.9(2)$
ZZ	$3.2730(4) \cdot 10^{0}$	$3.401(4) \cdot 10^{0}$	$+3.9(1)$
HZ	$1.22929(8) \cdot 10^{-1}$	$1.0557(8) \cdot 10^{-1}$	$-14.12(7)$
HH	$1.31569(5) \cdot 10^{-9}$	$42.9(4) \cdot 10^{-9}$ *	
W^+W^-Z	$9.609(5) \cdot 10^{0}$	$5.86(4) \cdot 10^{0}$	$-39.0(2)$
W^+W^-H	$2.1263(9) \cdot 10^{-1}$	$1.31(1) \cdot 10^{-1}$	$-38.4(5)$
ZZZ	$8.565(4) \cdot 10^{-2}$	$5.27(8) \cdot 10^{-2}$	$-38.5(9)$
HZZ	$1.4631(6) \cdot 10^{-2}$	$0.952(6) \cdot 10^{-2}$	$-34.9(4)$
HHZ	$6.083(2) \cdot 10^{-3}$	$2.95(3) \cdot 10^{-3}$	$-51.6(5)$
HHH	$2.3202(4) \cdot 10^{-9}$	$-1.0(2) \cdot 10^{-9}$ *	





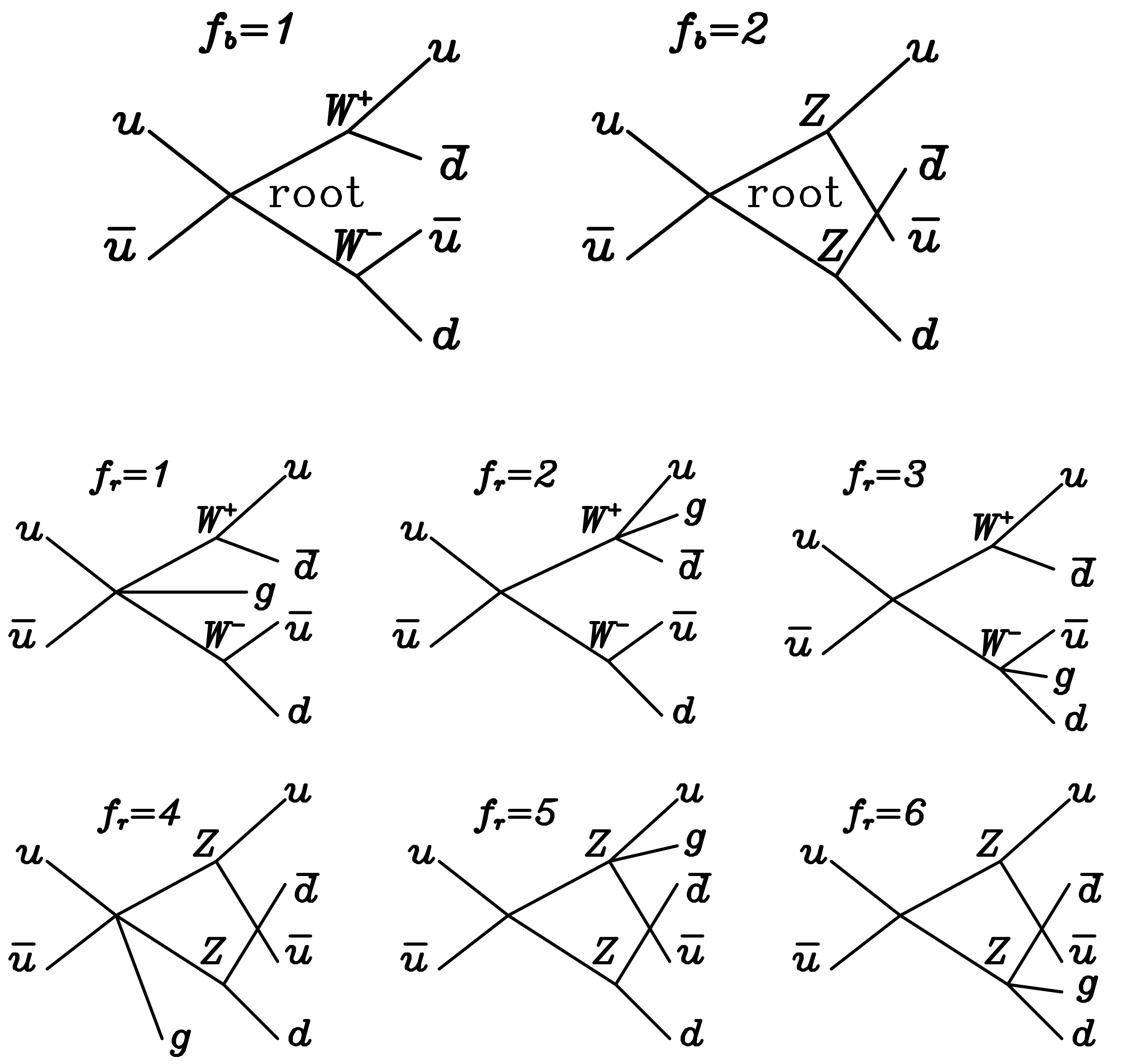
$\mu^+\mu^- \to X, \sqrt{s} = 10$ TeV	$\sigma^{\rm incl}_{\rm LO}$ [fb]	$\sigma^{\rm incl}_{\rm LO+ISR}$ [fb]	$\delta_{\rm ISR}$ [%]
W^+W^-	$5.8820(2) \cdot 10^{1}$	$7.295(7) \cdot 10^{1}$	$+24.0(1)$
ZZ	$3.2730(4) \cdot 10^{0}$	$4.119(4) \cdot 10^{0}$	$+25.8(1)$
HZ	$1.22929(8) \cdot 10^{-1}$	$1.8278(5) \cdot 10^{-1}$	$+48.69(4)$
W^+W^-Z	$9.609(5) \cdot 10^{0}$	$10.367(8) \cdot 10^{0}$	$+7.9(1)$
W^+W^-H	$2.1263(9) \cdot 10^{-1}$	$2.410(2) \cdot 10^{-1}$	$+13.3(1)$
ZZZ	$8.565(4) \cdot 10^{-2}$	$9.431(7) \cdot 10^{-2}$	$+10.1(1)$
HZZ	$1.4631(6) \cdot 10^{-2}$	$1.677(1) \cdot 10^{-2}$	$+14.62(8)$
HHZ	$6.083(2) \cdot 10^{-3}$	$6.916(3) \cdot 10^{-3}$	$+13.68(6)$

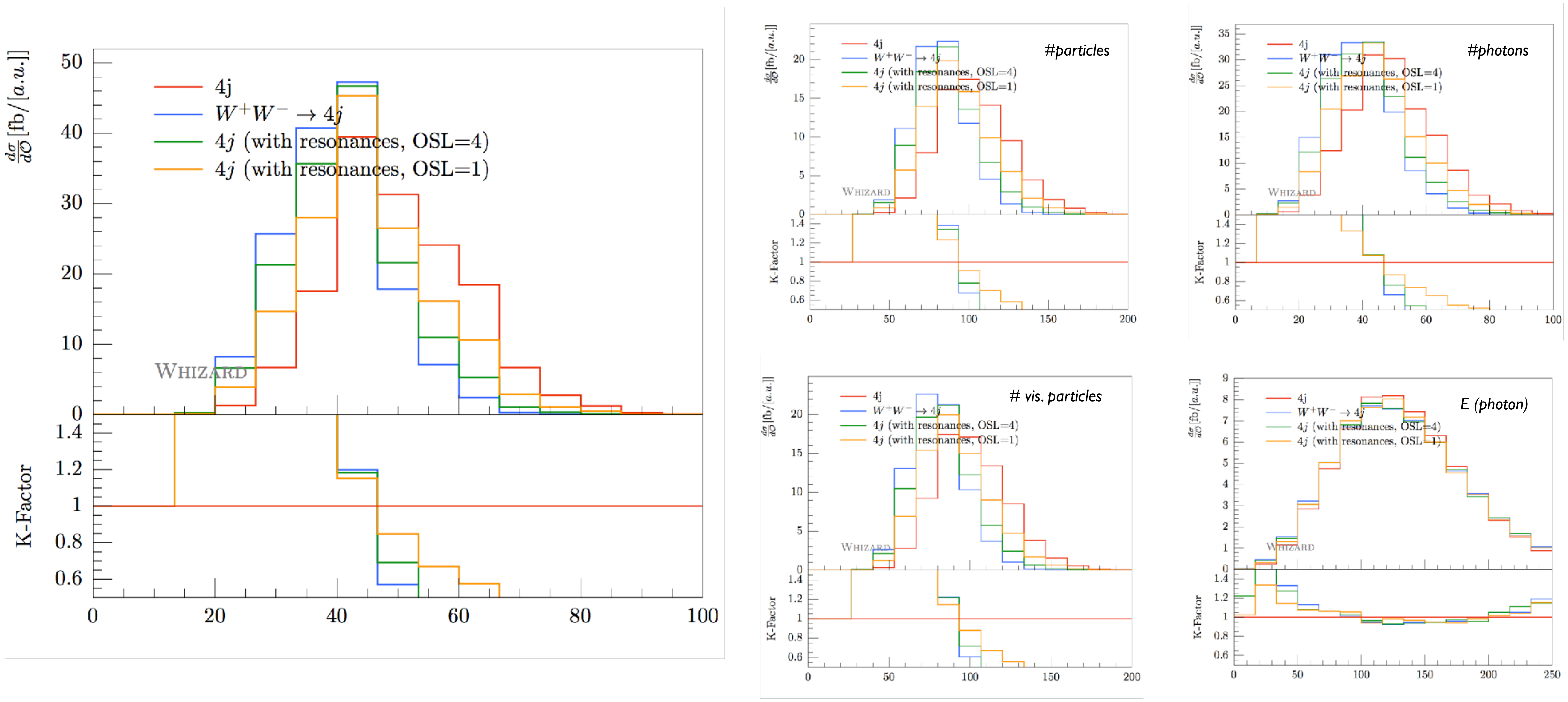
arXiv: 2208.09438

(Resonance) Matching to shower / hadronization


```
?resonance_history = true
resonance_on_shell_limit = 4
resonance_on_shell_turnoff = 1
resonance_background_factor = 1e-10
```

- Problem: $e^+e^- \to jjjj$ not dominated by highest α_s power, but by resonances $e^+e^- \to WW/ZZ \to (jj)(jj)$
- Solution: proper merging w/ resonant subprocesses by resonance histories
- `WHIZARD v2.6.0`: option to set resonance histories





↪ Talk by Zhijie Zhao on corresponding matching with PYTHIA8